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Homeland Security

N O T I C E

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15. Supplementary Notes

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16. Abstract (MAXIMUM 200 WORDS)

As an element in the Coast Guard's compliance strategy for decreasing greenhouse gases (GHG), and increasing the use of alternative fuels, the USCG Research & Development Center (RDC) tested a blend consisting of 16.1 percent biobutanol by volume (BU16), with regular E0 gasoline. BU16 is a renewable alternative gasoline fuel. The RDC tested BU16 on a USCG 25' Response Boat - Small (RB-S) powered by twin Honda Marine 225 HP, BF 225 engines at Training Center Yorktown, VA.

Biobutanol was obtained from Gevo, Inc., currently the sole United States supplier, working through a local distributor who blended and delivered it. Fuel quality was monitored throughout the test. Before the operational test, Honda conducted materials testing to examine engine compatibility with BU16, emissions testing, bench testing to determine the allowable mixing ratio for isobutanol, and on-water testing to assess engine performance.

Operational testing was conducted from 29 July 2013 to 31 July 2014. The RB-S underwent typical training missions and ran periodic baseline tests using E10 gasoline and BU16 for comparison. The RDC collected and analyzed engine performance data and crew observations of boat performance and maintenance. Details of the testing, and the conclusions and recommendations are included in the report.

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Biobutanol, isobutanol, BU16, alternative fuel, carbon footprint, emissions, greenhouse gas (GHG), Response Boat – Small (RB-S), Tier II testing, Energy Independence and Security Act (EISA), Oak Ridge National Laboratory (ORNL), Honda Marine, compatibility, Gevo	Distribution Statement A: Approved for Public Release; distribution is unlimited.		
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EXECUTIVE SUMMARY

Federal laws and mandates issued in recent years have focused attention towards reducing energy use and greenhouse gas (GHG) emissions, and increasing the use of renewable energy sources. Two prominent examples are the Energy Independence and Security Act (EISA) of 2007, which sets requirements for reducing energy and increasing the use of alternative fuels, and Executive Order (EO) 13514, which requires agencies to establish reduction targets for GHG. To meet these requirements, the United States Coast Guard (USCG) has commissioned studies with an overarching objective of reducing its carbon footprint through various approaches.

As part of this effort, the USCG Research & Development Center (RDC) initiated studies to examine alternative fuels, leading to the current Operational Testing Project. The first study addressed Alternative Fuel Options for Coast Guard (CG) boats, identifying options for replacing the currently used ten percent ethanol (E10) gasoline for outboards. The study identified a 16.1 percent mixture of biobutanol and gasoline (BU16) as an E10 alternative to test further. This earlier work suggests that biobutanol offers the Coast Guard a number of advantages, including:

- Biobutanol is a butanol that can be produced through processing of domestically grown crops, currently including corn and sugar cane, and in the future other biomass, such as fast-growing grasses and agricultural waste products.
- Biobutanol is a liquid alcohol that can be used in gasoline engines and can be a direct substitute for ethanol in blended gasoline without any engine conversion or modification.
- Biobutanol is compatible with the current gasoline distribution infrastructure and potentially can be blended at the refinery.
- Biobutanol would not require new or modified pipelines, blending facilities, storage tanks, or retail station pumps that Coast Guard sometimes uses for its fuel.
- Biobutanol is less affected than ethanol by problems associated with water absorption in the fuel, which can cause problems particularly in the marine environment.

A second study developed a test plan to test BU16 in CG boats, assessing boat performance, and the modifications required to use the fuel. The third study (and current project) executed this test plan to quantify implementation issues, benefits and impacts of using the alternative fuel in CG boats under typical mission conditions (Operational Testing). This report addresses the results of the operational testing.

The RDC and Honda Marine (Honda), the manufacturer for the outboard engines used on the RB-S, entered into a Cooperative Research and Development Agreement (CRADA) to study the use of BU16. Honda conducted materials testing to examine engine compatibility with BU16, testing to determine emissions characteristics, and bench testing to determine the allowable mixing ratio for isobutanol. Operational testing took place over a full year, to experience most typical environmental conditions and operational activities at the unit. Testing took place on a 25' Response Boat – Small (RB-S) operating out of USCG Training Center Yorktown, VA. Test data consisted of environmental data, engine/fuel system data, fuel chemistry, and crew observations. In addition, Oak Ridge National Laboratory (ORNL) provided expertise relating to the fuel specification, BU16.

Almost without exception the test team, RB-S coxswains and crew members perceived no performance difference when operating on BU16 fuel, compared to E10. The exception was a period where difficulty starting the engines in cold weather was experienced, which the test team attributed to test fuel chemistry

that had exceeded 16 percent butanol, rather than engine performance. RB-S performance is similar whether the fuel was E10 or BU16, or whether both fuels were mixed together.

Testing performed by Honda determined that emissions from the test engines met regulatory requirements when BU16 was in use, and emissions were equivalent for both BU16 and E10. Honda found no BU16 compatibility issues with the test engines. RB-S crewmembers detected no effect on maintenance between E10 or BU16 use. In addition, after testing for materials compatibility, and visually examining engine components following bench testing, Honda found no difference between the effects of E10 and BU16.

BU16 is not in current commercial use, so its use as a test fuel raised logistical and economic challenges that would normally be resolved by market forces for a commercially available fuel. Two issues that need to investigated further as BU 16 becomes commercially available are;

- Increasing percentage levels of butanol during extended storage noted during this study.
- Fuel distribution infrastructure materials compatibility.

Based on the testing in this study, BU16 is a suitable alternative fuel for the E10 currently used by the RB-S, within the environmental conditions experienced and for the test engines used in the study.

We recommend that the Coast Guard take some basic actions to position itself for the future availability of this fuel:

- Continue to monitor the commercial production capability of biobutanol producers as they bring their product to market.
- Once commercial availability has been established, consider adding biobutanol fuel capability as an added requirement for future outboard engine procurements.

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LIST OF ACRONYMS

AF	Alternative fuels
ASTM	American Society for Testing and Materials
ATON	Aids to navigation
BTL	Biomass-to-liquids
BU16	16 percent biobutanol/gasoline blend
CG	Coast Guard
CNG	Compressed natural gas
CO	Carbon monoxide
CO2	Carbon dioxide
CRADA	Cooperative research and development agreement
DHS	Department of Homeland Security
DIW	Dead in the water
DOE	Department of Energy
E10	10 percent ethanol/gasoline blend
EO	Executive order
EPA	Environmental Protection Agency
GHG	Greenhouse gas
GPH	Gallons per hour
GPS	Global positioning system
HP	Horsepower
HRA	Honda R&D Americas, Inc.
IMO	International Maritime Organization
KT	Knot
KW	Kilowatt
MFI	Multiport fuel injection
MLE	Maritime law enforcement
MPH	Miles per hour
MSDS	Material safety data sheet
NM	Nautical miles
NMEA	National Marine Electronics Association
NOx	Mono-nitrogen oxides NO and NO_2
ORNL	Oak Ridge National Laboratory
PSI	Pounds per square inch
RDC	Research & Development Center
RPM	Revolutions per minute
RVP	Reid vapor pressure
SAR	Search and rescue
SFC	Specific fuel consumption
SOG	Speed over ground
STBD	Starboard

LIST OF ACRONYMS (Continued)

TCTO	Time compliance technical order
TRACEN	Training Center
USCG	United States Coast Guard
VDC	Volts direct current
WF	Weighting factor
WOT	Wide open throttle
WX	Weather station

1 BACKGROUND

In recent years, the International Maritime Organization (IMO), Environmental Protection Agency (EPA), the United States (US) Congress, and the White House have established policies designed to reduce air pollutants, reduce carbon footprint and encourage the use of alternative fuels. Some of these actions, particularly in the federal domain, influenced initiation of this project and are described below.

1.1 Federal Mandates and Greenhouse Gas Emissions

The Energy Independence and Security Act (EISA) of 2007 (P.L. 110-140, H.R. 6) aims to increase U.S. energy security, increase the use of biofuels, and improve vehicle fuel economy. Using 2005 as a baseline, EISA requires federal agencies to reduce facility energy consumption by 30 percent, reduce petroleum consumption by 20 percent, and increase alternative fuel consumption by 10 percent by 2015.

Executive Order (EO) 13514; Federal Leadership in Environmental, Energy, and Economic Performance (2009), requires agency-wide reduction goals for energy, water and waste. E.O. 13514 also requires agencies to establish reduction targets for direct greenhouse gas (GHG) emissions from sources that are owned or controlled by the Federal agency, defined as Scope 1 emissions. The Department of Homeland Security (DHS) Strategic Sustainability Performance Plan (DHS 2011) sets a 25 percent GHG Scope 1&2 reduction goal for the United States Coast Guard (USCG) by FY 2020 (relative to its FY 2008 baseline). An example of Scope 1 emissions are those from Coast Guard (CG) boats. To achieve this GHG reduction goal, DHS developed a high-level approach that includes short-, medium-, and long-term initiatives. These activities build on existing efforts to reduce the energy intensity of its operations, increase the utilization of alternative fuels (AFs), and purchase renewable energy. The DHS plan identifies increased use of AFs in alternative fuel vehicles and flex-fuel vehicles. To support these goals, the CG has commissioned studies designed to research and test alternative fuels, with an eye towards greater accountability of fleet fuel usage, reduced greenhouse emissions and future cost savings.

1.2 Alternative Fuels

Alternative fuels are any fuels other than traditional petroleum-based gasoline or diesel. The alternative fuel tested in this project was a 16.1 percent by volume blend of biobutanol (isobutanol) in gasoline (BU16). This blend was determined by a prior Research & Development Center (RDC) study, described as Project 1 below. Biobutanol and petrobutanol have the same chemical properties; however biobutanol can be produced from various types of biomass. Currently, butanol is primarily used as an industrial solvent in products such as lacquers and enamels.

Butanol is a 4-carbon alcohol, which is also known as butyl alcohol, and can refer to any of the four isomeric alcohols of formula C_4H_9OH. Ethanol and isobutanol are both alcohols and have some similarities, such as containing fuel-bound oxygen, being polar molecules, and being fully miscible with gasoline on their own, and fully miscible as a mixture in gasoline blends. Like ethanol, biobutanol is a liquid alcohol fuel that can be used in today's gasoline-powered internal combustion engines. Butanol has a higher energy density than ethanol, but in gasoline blends with the same oxygen content, the energy density is approximately the same. This study compared E10 with BU16, which have approximately the same energy density, thus there is no expected fuel economy benefit.

One of the main differences between ethanol and isobutanol mixtures is their interaction with water. If the fuel mixtures are exposed to a sufficient amount of water to form an aqueous phase, either through absorption from humid air or through exposure to liquid water (exposure to rain, for example), ethanol preferentially goes to the aqueous phase. This significantly changes the fuel properties of the fuel remaining in the non-aqueous phase, particularly the octane number. In contrast, isobutanol primarily stays in the non-aqueous phase, allowing the aqueous phase to be removed from the fuel with minimal impact on fuel properties. This difference in the interactions with water is one of the reasons why isobutanol may be preferred in the marine environment, where fuel is continuously subject to exposure to water. Recent breakthroughs in biobutanol production technology, namely the discovery and development of genetically-modified microorganisms, have made it possible for biobutanol to begin to replace ethanol in large quantities. Biobutanol, isobutanol and butanol, are used synonymously in this report.

Engines running on biofuels emit carbon dioxide (CO_2), the primary constituent of greenhouse gas emissions. Fossil fuel use produces CO_2 from carbon that has been stored underground, producing a net CO_2 addition to the atmosphere. Because biofuels are derived from plants, which consume atmospheric CO_2 during their growth, the release of CO_2 when biofuels are burned effectively recycles atmospheric CO_2 that was previously absorbed from the atmosphere. Biofuels still use fossil fuels such as coal and natural gas for their production, so they currently represent a small net atmospheric CO_2 source. Replacing traditional fuels with biofuels however, can reduce the carbon footprint. The RDC initiated several studies to examine alternative fuels, with two of the studies leading to the current Operational Testing Project. These studies are described below.

2 OVERVIEW OF THE OPERATIONAL TESTING PROJECT

The Operational Testing Project is the third in a series of RDC studies that examined the use of alternative fuels as potential substitutes for E10 gasoline. This report presents the results of testing an isobutanol-based alternative fuel.

2.1 Project 1: Alternative Fuel Study

The first RDC study addressed alternative fuel options for CG vessels, identifying alternative fuels, appropriate boat classes, and locations for testing. Liquid and gaseous alternative fuels, were evaluated and ranked, and a comprehensive initial list of eleven gasoline alternative fuels was developed from those listed on the Department of Energy's (DOE) Web site (http://www.afdc.energy.gov/afdc/) and fuels recommended by CG subject matter experts (SMEs). This list was reduced using four criteria:

1. Affordability.
2. Availability.
3. Safety.
4. Potential Carbon Footprint Reduction.

Using these criteria, the initial list was reduced to the following alternative fuels for further analysis:

1. Compressed natural gas (CNG).
2. Liquid Natural Gas (LNG).
3. Ethanol and ethanol mixtures.
4. Biobutanol.
5. Biomass-to-liquids (BTL).

2.1.1 Test Fuel

The above five candidates were evaluated against 25 attributes in a fuel evaluation matrix (6APPENDIX A), using E10 gasoline as a baseline fuel for comparison. The RDC, with sponsor and stakeholder input, selected a 16.1 percent blend of biobutanol with gasoline (BU16) as the test fuel. Gaseous alternative fuels (CNG and LNG) were eliminated due to low volumetric energy density, issues associated with locating fuel storage tanks, the costly and extensive modifications required to the fuel system and the engines, and the perceived risk associated with high pressure fuel. BTL was considered high risk because it was not readily available for test purposes, nor was there much experience with it in the transportation sector. The biobutanol used for the BU16 blend was made from a process currently under development by Gevo, Inc. No other suppliers for biobutanol are currently producing in the U.S.

2.1.2 Test Platform and Location

The RDC selected the 25’ Response Boat - Small (RB-S) with Honda Marine (Honda) outboard engines as the BU16 test platform (Figure 1), because (1) Honda engines are the most widely used brand of outboard by the CG, and (2) current deployment of the RB-S offered a large number of locations where testing might be conducted. The RDC designated USCG Training Center (TRACEN) Yorktown, VA as the test unit, for three reasons:

- A large number of RB-S platforms available;
- avoidance of operational impact on a USCG SAR or MLE mission unit, such as a small boat station; and
- availability of platforms for other testing related to this project.

Unless otherwise specified, the term “RB-S” is used in this report to refer to the test boat, CG 25417, located at TRACEN Yorktown. Table 1 shows the RB-S class characteristics.

Figure 1. 25’ RB-S.

Table 1. Operational and physical characteristics of 25' RB-S Defender Class.

Operational Characteristics		Physical Characteristics	
Max Range @ Cruise Speed	175 NM[1] (A Class) 150 NM (B Class)	LOA[2]	29'-4" (A Class) 29'-6.5" (B Class)
Max Speed	46 knots @ 6000 RPM[3]	Beam Overall (includes collar)	8'-6"
Cruise Speed	35 knots @ 4500 RPM	Operational Draft (DIW[4] with engines vertical)	3'-3"
Maximum Operating Distance from Shore	10 NM	Propulsion	Twin Honda Marine 4-stroke outboard engines, 225 HP[5] each, Model BF225
Fuel Consumption (both engines) @ 6000 RPM	40 GPH[6] (A Class) 44 GPH (B Class)	Generator	NA
Fuel Consumption (both engines) @ 4500 RPM	28 GPH (A Class) 20 GPH (B Class)	Generator Engine	NA
		Displacement (without crew)	7,400 pounds
		Fuel Tank Capacity	125 gal (A Class) 105 gal (B Class)
		Number of Fuel Tanks	1
		Crew/Passenger Capacity (seated)	Four crew, six passengers
		Deckhouse	Aluminum
		Hull	Aluminum

[1]nautical mile
[2]length overall
[3]revolutions per minute
[4]dead in the water
[5]horsepower
[6]gallons per hour

2.1.3 Honda Marine CRADA

The RDC signed a Cooperative Research and Development Agreement (CRADA) with Honda R&D Americas, Inc. on 9 June 2011, to provide technical assistance prior to and during the testing. CRADAs are authorized by the Federal Technology Transfer Act of 1986 (Public Law 99-502, codified at 15 U.S.C. 3710(a), as amended. A CRADA promotes the transfer of technology to the private sector for commercial use, as well as specified research or development efforts that are consistent with the missions of the federal laboratories that are party to the CRADA. The federal party or parties agree to share research resources with one or more non-federal parties. The federal laboratories can contribute all warranted and available resources except funds. Honda provided technical input for the fuel selection and test plan, and performed materials testing, bench testing and limited field testing.

2.1.4 Oak Ridge National Laboratory

The RDC established an interagency agreement with the DOE to obtain technical support from the Oak Ridge National Laboratory (ORNL) for the testing. ORNL provided:

- Guidance to RDC on the test fuel blend,
- Input and review of a protocol to assure fuel quality and compatibility during the tests,
- Review of fuel issues during operational testing.

2.2 Project 2: Test Plan Development

A second RDC study was conducted to develop a BU16 Test Plan (Appendix B). In addition, a draft Time Compliance Change Order (TCTO) (Appendix C) was prepared, which described planned changes to the RB-S to prepare for testing. Section 3.2 discusses the modifications made. The protocol developed for testing alternative fuels included four phases: materials, bench, field, and operational testing, as noted below.

- **Materials Testing** to determine the compatibly of the engine fuel system and fuel-wetted parts with BU16 and the maximum percentage of butanol based on materials. Honda performed this testing and refers to it as component function testing in their report (Appendix D).
- **Bench Testing** to ensure the engines will operate satisfactorily on BU16 and determine if engine adjustments were needed, the maximum percentage of butanol for performance and emission characteristics. Honda refers to this testing as engine performance testing in their report (Appendix D). A subset of the engine performance testing that was performed on the water by Honda is referred to as endurance testing in their report (Appendix E).
- **Field Testing** to ensure the entire fuel system (i.e., components from the fuel tank to the engines) is compatible with the biobutanol blend, and to establish baselines on the normal fuel (E10) and the test fuel (BU16) for comparison purposes. This testing was accomplished by the RDC test team and TRACEN Yorktown personnel. For this project, field testing was an early phase of operational testing.
- **Operational Testing** to determine the feasibility of using BU16 in CG boats. This testing was accomplished by the test team and TRACEN Yorktown personnel.

2.3 Project 3: Operational Testing

The current RDC study carried the investigation of alternative fuels forward to the next phase, executing the test plan developed in the previous study. The objective of this phase was to identify and quantify any implementation issues, benefits and impacts of using BU16. Testing focused on operations, engine performance, engine maintenance, and crew health and safety, with the goal of identifying impacts that would exceed nominal operating parameters. In the long-term, the purpose of operational testing was to contribute to the CG's overall goal of achieving the carbon reduction mandate described earlier, by converting a portion of its boat fleet to a renewable fuel that might offer benefits not realized with current E10 use.

3 PREPARATIONS FOR OPERATIONAL TESTING

The following major activities were completed before operational testing began:

- Honda testing:
  - Honda Testing Process.
  - Performance & Component Testing.
  - Endurance Testing.
- Installation of the data collection system on the RB-S.

- Compatibility of the RB-S Fuel system.
- Test Fuel Logistics.

3.1 Honda Testing

3.1.1 Honda Testing Process

Honda conducted their testing to determine the degree to which engine performance, component function and the durability/reliability of multiport fuel injected outboard engines would be influenced by using a biobutanol-mixed fuel.

As shown in Figure 1, this project consisted of three steps. Step 1 consisted of engine performance tests and component function tests conducted by Honda. Step 2 included the evaluation of the results of the tests in Step 1 and the endurance testing of performance and components. Based on the results of Step 2, Honda made an official recommendation to the CG that it proceed with their yearlong test at TRACEN Yorktown. Step 3 consisted of the operational testing described in this report.

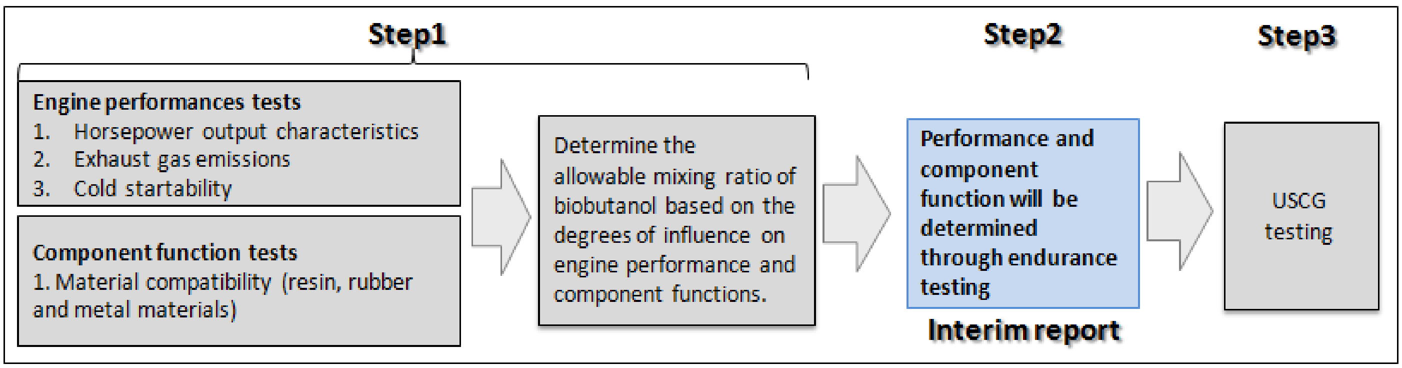

Figure 2. Honda testing process.

3.1.2 Performance and Component Function Testing

Honda performed engine performance (bench) and component function (materials) tests to determine the allowable mixing ratio for a biobutanol/gasoline blended fuel for its multiport fuel injection (MFI) outboard engines currently available on the market. Honda reported the results of these tests in 6APPENDIX D. Honda planned their testing to focus on the engine performance tests and component functions shown in Figure 3. Honda also conducted durability/reliability testing (endurance testing), to determine the degree to which 16.1 percent biobutanol/gasoline blended fuel would affect engine and component performance. From the results in both areas of testing, Honda concluded:

- The mixing ratio of butanol to be used for the bench durability/reliability tests of MFI outboard engines is limited to 16.5 percent by volume due to the cold startability at -15C as a restrictive factor.
- The use of biobutanol, mixed with gasoline (87 octane conventional clear gasoline base) at 16.1 percent by volume does not adversely affect any of the systems of the Honda MFI four-stroke outboard engine. Judging by the data gathered in this test, Honda indicated that the CG could proceed with operational testing on the test engines.

Item	Gasoline (E0)		Butanol		Ethanol (E10)
Energy density [%]	100	>	84	>	66
Oxygen content[wt %]	0	<	21.6	<	34.7
Stoichiometrical air-fuel mixture ratio	14.6	>	11.2	>	9
Pump Octane [(RON+MON)/2]	86	<	98	<	102
Reid vapor pressure RVP [kPa]	44 - 78	>	3.4	<	16
Hygroscopicity property	None	<	Low	<	High
Alcohol content	Not contained	>	Contained	=	Contained

Items checked for determination of allowable mixing ratio	
Engine performance tests	• Horsepower output characteristics • Oil Consumption • Idle Stability •Cold Start ability
Component function tests	• Corrosion of metal components due to water
	• Corrosion of metal components due to alcohol • Swelling of resin and rubber components due to alcohol.

Figure 3. Comparison of fuel characteristics and items checked to determine allowable mixing ratio.

The subsections below present additional conclusions by Honda from their testing.

3.1.2.1 *Butanol Compatibility*

Butanol is less detrimental than ethanol to the materials used in outboard engines. Butanol also has lower affinity with water and is therefore promising as an alternative fuel for outboard engines, which are inherently vulnerable to contact with water.

3.1.2.2 *Oxygen Content*

Oxygen content has the greatest influence on engine performance. The oxygen in butanol-mixed fuel is lower than ethanol-mixed fuel and the resulting higher energy density allows for use of higher mixing ratios than ethanol. Accordingly, CO_2 can be reduced. (The oxygen content of E10 is roughly the same as that of gasoline containing 16.5 percent by volume of butanol.)

3.1.2.3 *Allowable Butanol Blend*

The allowable mixing ratio of butanol for MFI outboard engines is 16.5 percent by volume or less, which is limited by its cold start times at -15 °C (5 °Fahrenheit) as a restrictive factor. The allowable mixing ratio of butanol for MFI outboard engines based on materials compatibility is 20 percent by volume or less, which is limited by resin materials (using the resin known as PA12 or nylon 12 - See Section 3.1.2.8, addressing alcohol swelling). At mixtures of up to 50 percent butanol, the horsepower (HP) output was equivalent to that of the baseline E0. At the target 16.5 percent butanol, the HP was slightly higher than with E10.

3.1.2.4 *Exhaust Gas Emissions*

At mixtures of up to 50 percent, emissions were within regulatory limits. At the target 16.5 percent, the carbon monoxide (CO) was slightly lower than with E10, and both were lower than E0. The NOx and CO_2 levels were slightly higher for BU16 than for E10 and both were slightly higher than E0.

3.1.2.5 Cold Start Time

Comparable cold-start times were found for E10 up to the 16.5 percent butanol blend. Higher butanol blends required increased start times. Honda concluded that start times would be acceptable at higher butanol percentages by changing the Engine Control Unit (ECU) starting specifications.

3.1.2.6 Water Corrosion of Metal Components

Corrosion of metal components occurs in a condition where water undergoes phase separation from fuel. Corrosion of metal components in E10 occurs at a higher percentage of water than in regular gasoline (E0). Likewise, in butanol, corrosion of metal components in B50 occurs at a higher percentage of water than in B20.

3.1.2.7 Alcohol Corrosion of Metal Components

Butanol did not cause an aluminum corrosive reaction at any ratio (from 0 to 100 percent by volume.)

3.1.2.8 Alcohol Swelling of Resin and Rubber Components

There was no impact on rubber or most resin materials (up to 100 percent butanol). One resin material, PA-12, was a restrictive factor and was acceptable up to a 20 percent blend. PA-12 is a polyamide resin, a form of nylon that can be molded into plastic pipes, tubes, and hoses to carry vapors, fuel, and other liquids. It is a key ingredient in nylon used to make fuel lines, brake lines, pipelines, and various auto/engine parts. Honda concluded that this limit could be increased to a higher percentage by further testing and/or a change in material specifications by adopting the appropriate materials.

3.1.3 Endurance Testing

Honda performed endurance testing to determine the degree to which engine performance, component function, and the durability/reliability of MFI outboard engines would be influenced using a biobutanol-mixed fuel. The Honda report detailing these tests is included in 6APPENDIX E. This testing took place on the water in Florida from January to April 2013 in a variety of environmental conditions, including temperatures from 50 to 84 °F, and relative humidity from 0 to 92 percent.

To accomplish the testing, Honda conducted two different endurance tests on two separate engines. At the beginning and conclusion of the test, both engines were disassembled and precision measurements on key components were taken and documented. The engine measurement data were analyzed to determine if the use of biobutanol had any adverse effects, including abnormal wear, on specific engine components. Both engines were maintained in accordance with the manufacturer's guidelines. Both engines used in the endurance tests were V6, 225 HP Honda four-stroke outboards, with no special modifications made to either engine. The fuel used for both tests was an 87 octane conventional clear gasoline base mixed with biobutanol at a 16.1 percent ratio by volume. The first engine was tested under conditions that simulated average use by a normal customer, and the second engine was operated at full throttle for the duration of the test.

Honda concluded that the use of biobutanol, when mixed with gasoline at a 16.1percent ratio, does not adversely affect any of the systems of the Honda MFI four-stroke outboard engine. Honda concluded that the Coast Guard could proceed with operational testing. The subsections below present additional conclusions from the testing.

3.1.3.1 Fuel System Inspection

Honda determined that biobutanol use had no observable adverse effects on its fuel system components, and biobutanol effects were the same as those from conventional E0-E10 gasoline.

3.1.3.2 Performance and Internal Engine Components Inspection

Honda reported that power, performance, top speed, and oil consumption were all within acceptable limits on both engines at the conclusion of the test. Carbon build up on the piston crowns and the combustion chambers was within acceptable limits. There was no visual evidence of damage or excessive wear to any internal engine components. The acceptable condition of the internal engine components was validated by precision measurements - all measurements taken were within acceptable limits. No adverse effects to the internal engine components were caused by the use of biobutanol.

3.1.3.3 Oil Performance

Honda sampled and analyzed engine oil every 50 hours during the endurance test, and reported that biobutanol use had no negative effect on the engine oil.

3.2 Modifications to the RB-S

3.2.1 Data Collection System

The approach for collecting data from the Honda engines evolved during the project. Initially, the test team planned to use software provided by Honda, called Dr. H. Upon examination, however, the test team determined that Dr. H would not capture the required engine parameters. At about the same time, Honda changed a key engineering point of contact, driving a change in direction towards collecting engine data via the National Marine Electronics Association 2000 (NMEA 2000) Network. As the test team explored this new approach, it discovered that the port Honda engine was not equipped with a NMEA 2000 interface that would allow connection to the network. A compromise solution was devised to collect port engine data via analog-to-NMEA 2000 translators to measure RPM and fuel flow.

After the initial network installation, the test team added a NMEA 2000-compatible Global Positioning System/Weather (GPS/WX) sensor (PB200), and a computer specifically configured to record the NMEA 2000 data. The PB200 is an integrated collection of sensors used to record environmental data (temperature, wind speed, etc.) as well as GPS position, course, speed, and boat roll and pitch. The computer, made by Chetco Inc., ran a software package called vDash®, and featured a special input port to connect to the NMEA 2000 network. The computer was connected to a wireless router, allowing the test team to remotely monitor the network. This finalized the data collection system installation in July 2013 to begin operational testing.

In September 2013, the port RB-S Honda engine was replaced due to a casualty unrelated to the testing. The replacement engine was a newer model with a NMEA 2000 data port. The test team connected the new engine to the NMEA 2000 network via a proprietary Honda cable, resulting in a data setup that matched the starboard engine. The test engineer reprogrammed the computer to accept the new data from the port engine.

The final configuration for the NMEA networked data collection system is shown in Figure 4. The draft RB-S TCTO included installation of a Flo-scan fuel meter, to bring the fuel flow signal to the NMEA network; however the Flo-scan already existed in the RB-S fuel system. After the port engine was replaced

as described above, the tap to the Flo-scan was removed, and the port engine fuel data was captured from the NMEA 2000 data port directly.

Once the data collection system was up and running, two other problems surfaced.

- If the Chetco computer was powered down by opening the circuit breaker, rather than via the computer operating system, it froze upon startup. To restart the system, the test engineer remotely walked the boat crewman through the required steps.
- Interaction between the vDash software and the Windows operating system sometimes caused the NMEA data coming across the serial port to be interpreted as a hardware install request, automatically installing a mouse driver on the port. The data flowing through the port caused this "virtual mouse" to randomly click over the screen, which shut down the data collection system and ended testing. Although the test engineer was able to log on remotely to restart the system, this did not prevent occasional reoccurrences.

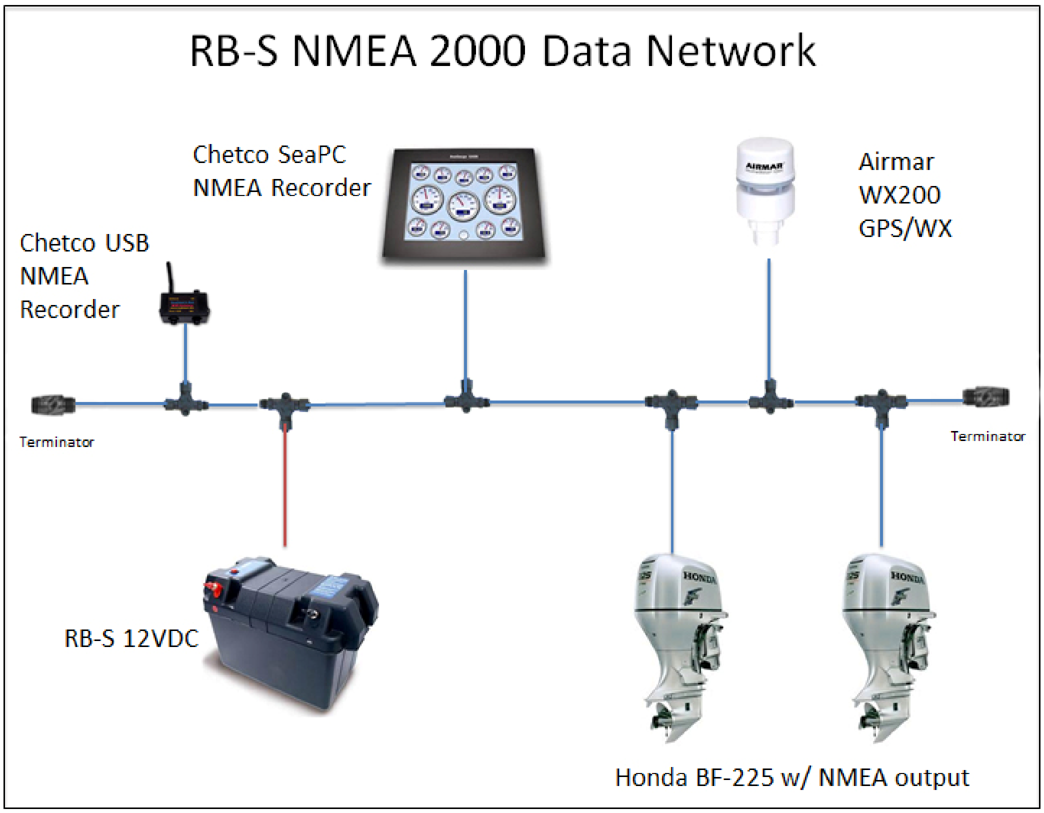

Figure 4. NMEA 2000 network.

3.3 RB-S Fuel System

Experts generally believe that the material compatibility challenges with isobutanol are less severe than those posed by ethanol for engine fuel systems designed for gasoline, such as the RB-S. Therefore, BU16 was expected to have fewer materials compatibility issues than E10 (Kass et al. 2013, Kass et al. 2014, Kass et al. 2014). Based on the Honda testing, no changes were made to the engines at the beginning of operational testing at TRACEN Yorktown. A list of wetted fuel parts was prepared prior to this project to support a materials audit, and Honda testing examined resin and rubber components on the list to identify any potential compatibility issues such as alcohol or water corrosion of metal engine components, and

alcohol swelling. As noted in Section 3.1, Honda concluded that no adverse reactions were found in any of these areas, with butanol blends as high as 20 percent. Honda also disassembled and inspected engine parts at the conclusion of endurance testing and found no adverse effects.

3.3.1 Test Preparation Costs

The costs for preparing the RB-S for operational testing are provided in Table 2. These costs include parts and contract labor for installing the data collection system described below. Honda required no engine modifications, so all costs are related to the data collection system. Labor costs by TRACEN Yorktown and the RDC test team are not included.

Table 2. BU16 test preparation costs.

ITEM	COST
NMEA 2000 network parts	$395
Miscellaneous installation hardware	$325
Chetco SeaPC data computer	$3,250
Chetco USB NMEA recorder	$595
Airmar GPS/WX station	$1,150
TOTAL	**$5,715**

3.4 Test Fuel Logistics

Biobutanol for the test fuel blend was provided by the only U.S. supplier at this time, Gevo, Inc. Gevo contracted with Domestic Fuels (Domestic), a local fuel supplier in the Yorktown, VA area to blend and deliver the BU16. On 23 May 2013, Domestic mixed the biobutanol with E0 summer gasoline to make 10,000 gallons of BU16, to be stored in a tank at Domestic. Domestic delivered the fuel on demand to TRACEN Yorktown by tank truck. Upon arrival the fuel was pumped into a trailerable 500 gallon storage tank. USCG personnel pumped the BU16 directly from the trailerable tank into the boat fuel tank as needed. The fuel quality was monitored via fuel sample analyses performed by both the RDC and the fuel supplier (Gevo) through independent testing laboratories. Fuel sample analysis results are described in Section 4.5.

4 OPERATIONAL TESTING & RESULTS

Operational testing began on 29 July 2013 and concluded on 31 July 2014, after 418 underway hours, and after 1190 gallons of BU16 were consumed on the RB-S. During this testing, the RB-S performed typical duties such as coxswain training, and made field test runs to generate baseline data using E10 and BU16. BU16 testing focused on operations, engine performance, engine maintenance, and crew health and safety, with the goal of identifying impacts that would exceed nominal operating parameters.

The test team and technicians from Honda met at TRACEN Yorktown on 9 September 2014 to replace engine fuel components with new parts on the newer (port) engine. After the engines were demonstrated to be running properly, the test team removed the data acquisition equipment, returning the RB-S to its pre-test condition.

4.1 Field Testing

For the first phase of operational testing, the test team conducted field testing at Yorktown from 21 July to 28 July 2013, running baseline tests and inspecting the boat during and after operation to check for potential problems. After configuring the engines and data collection system, and resolving residual setup issues, the test team adopted the following protocol to accomplish field and baseline testing on the RB-S.

1. A prolonged warm-up at idle (~1 hour) at the pier.
2. Slow-cruise at < 10 kts (minimum 1 hour).
3. Fast-cruise at ~ 25 kts (minimum 1 hour).
4. Wide-open throttle (minimum 1 hour).

The RB-S performed well using BU16 during the initial test, and no problems were detected. Additional baseline tests were performed throughout the year-long operational test period (see Table 3) to capture the most usable data for comparison between E10 and BU16.

Table 3. RB-S baseline tests.

Test Week	BU-16	E10
26 JUN 2013	✓	✓
23 JUL 2013	✓	✓
24 SEP 2013	✓	
28 OCT 2013	✓	
2 DEC 2013	✓	
13 JAN 2014	✓	
25 FEB 2014	✓	✓
14 MAY 2014	✓	✓
18 JUN 2014	✓	
22 JUL 2014	✓	✓✓ (2)

4.2 Fuel Effect on Boat Performance

Engine performance characteristics were assessed by monitoring the boat speed over ground (SOG), port and starboard (STBD) engine RPM, and fuel consumption in gallons per hour (GPH). Multiple operational field tests were carried out using each fuel (E10 and BU16) over the test period. During the tests, data elements (including the desired engine performance data) were recorded to a Windows-based Chetco computer. These binary data files were then parsed using the vDash software to produce spreadsheets containing the desired parameters. The data files were analyzed and filtered to only include reasonably long sample durations for each RPM range (1 thru 4 above). These samples were chosen from periods where port and STBD engine RPMs were synchronized and stable. Figure 5 shows an example of the chosen segments (in four vertical color bands). Figure 6 displays the resulting sample segments.

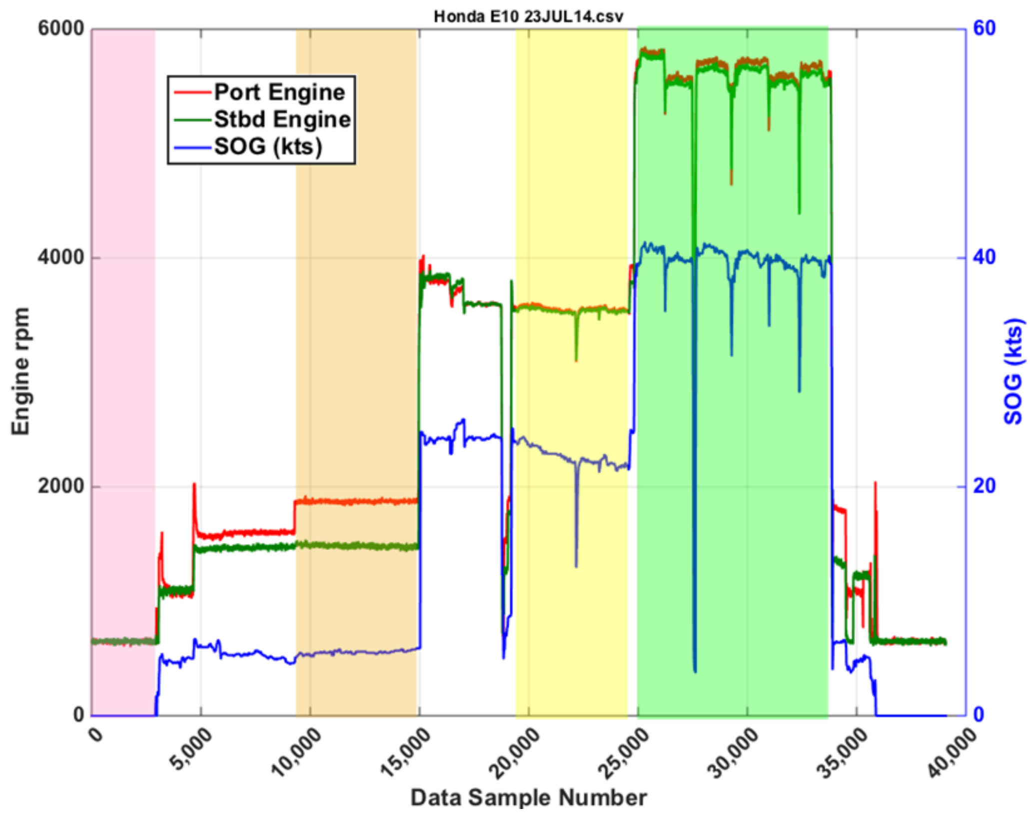

Figure 5. USCG data from Honda engines showing example of four data segments.

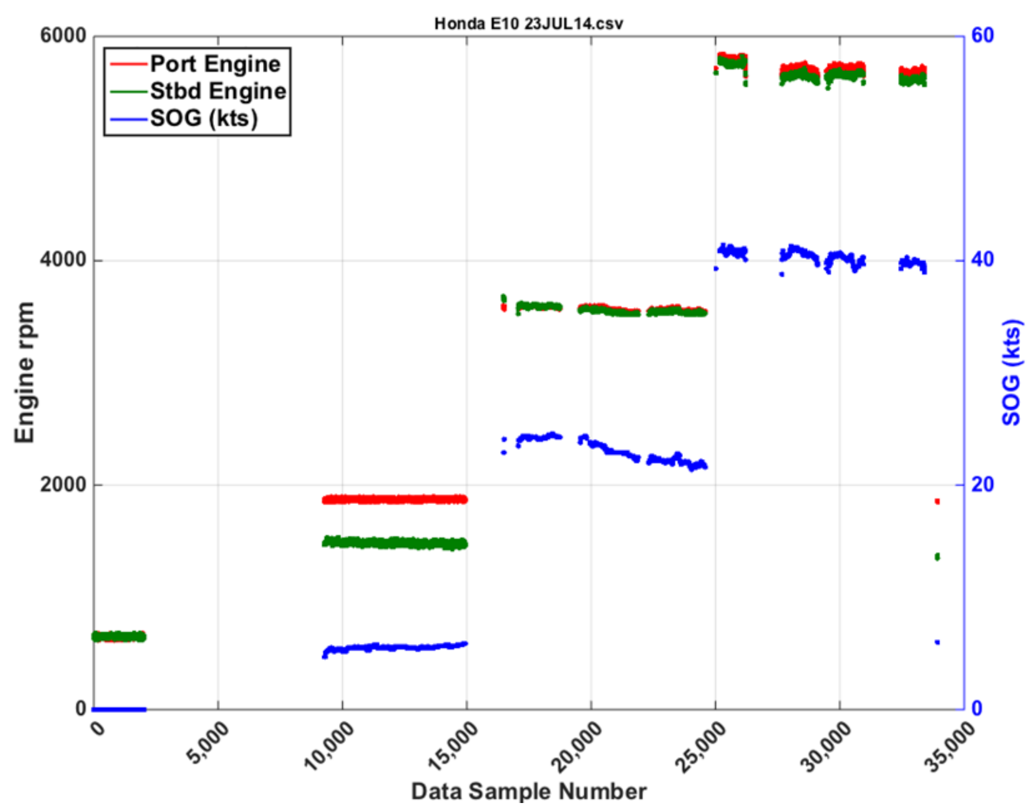

Figure 6. USCG data from Honda engines showing only the selected data segments.

The test team selected the data segments in the above manner due to the operational nature of the testing; the tests were conducted in the normal operating area, which included an active shipping channel. The coxswains therefore had to make course and speed changes to avoid vessel traffic, especially during the wide-open throttle tests. Once the desired data segments were identified, each segment was passed through a 3σ filter to remove data outliers in the segment.[1] Table 4 shows the number of data segments for the desired RPM range, as well as the total number of samples recorded for all of these segments.

Table 4. List of data segments and number of samples.

	E10		BU16	
RPM Range	Data Segments	Total Samples	Data Segments	Total Samples
IDLE	4	28801	5	48000
SLOW-CRUISE	4	27220	5	30044
FAST-CRUISE	4	25060	4	19919
WIDE-OPEN THROTTLE	4	24169	4	26055

The averaged engine speed (RPM) versus fuel flow rate (GPH) points are shown in Figure 7, along with a reference line to compare with similar existing test data from Honda, and available on their website. Honda has not performed fuel-consumption testing on the RB-S, so the reference line represents data for a 22' Hewescraft 220 with a similar hull design, a weight of 2600 lbs, and powered by a single BF225 Honda engine. The RB-S is outfitted with twin BF225 engines and has a weight (without crew) of 7,400 lbs, and therefore different load characteristics. As the graph shows however, the data collected during the operational tests agrees well with Honda's testing.

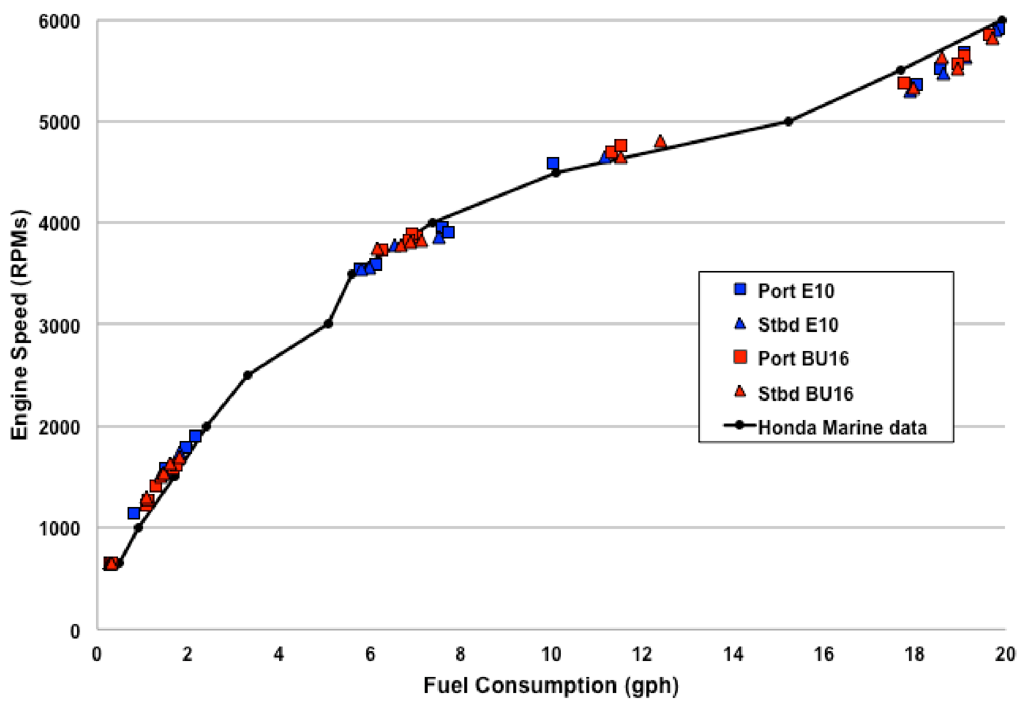

Figure 7. Honda engine speed vs. fuel consumption.

[1] For each data vector, the mean and standard deviation was calculated for each segment (when the data was relatively constant). Any data point that was more than 3 standard deviations from the mean was deleted. This was necessary to remove data points that would improperly skew the results. Each data vector was filtered independently to remove outliers, however if an outlier was found in any of the 3 data vectors, that time sample was deleted for all 3 data vectors, to maintain alignment between the vectors.

The fuel consumption comparison shows that boat performance will be similar for both BU16 and E10. The variances between the two engines are greater than the variances between the two fuels. This difference seen in the fuel consumption vs. engine speed graph agrees with Honda's findings in their interim BU16 CRADA report (USCG & HRA, 2013).

4.3 Fuel Effect on Engine/Boat Maintenance

The test team and boat crews noted no impact from BU16 on the maintenance required for the Honda engines or the RB-S during the operational testing.

4.4 Emissions

Honda conducted engine exhaust emissions testing in conjunction with their bench testing. For mixtures up to 25 percent, Honda used the testing methods prescribed by the EPA in 40 CFR, Part 1065, Subpart I. For mixtures 25 percent and above, Honda provided emissions testing data for reference purposes only. Honda concluded that for the engines tested, the allowable mixing ratio that satisfied existing exhaust emission regulation values was 50 percent butanol by volume or less. Honda concluded further that for their target blend of 16.5 percent butanol, both emissions and specific fuel consumption (SFC) were equivalent to the levels measured with E10 gasoline. The target blend was determined as the allowable mixing ratio of butanol that ensures engine startability equivalent to E10 gasoline when used.

4.5 Fuel Quality

Fuel samples were collected by the RDC and Gevo/Domestic for analysis by independent testing laboratories. Gevo was required to provide the fuel at 16.1 percent biobutanol (isobutanol) blended with 87 octane regular unleaded gasoline (E0). BU16 is a developmental alternative fuel, and at the beginning of the test, there was no approved ASTM specification for the butanol component that would be mixed with the gasoline. The RDC participated in an ASTM technical working group that developed the butanol specification (ASTM D7862), which was vetted and published in August 2013. The blended fuel (BU16) used in the operational test was mixed prior to the specification approval, but the butanol used in the blend was in compliance with the specification.

During the test period, BU16 was compared against ASTM-D4814, which is an approved standard for automotive fuels for ground vehicles equipped with spark-ignition engines and includes blends with oxygenates. Comparing the test results to this standard provided assurance that the fuel was in close compliance with a specification suitable for spark-ignition engine fuels, and theoretically should result in satisfactory operation. Testing also allowed trends in the test parameters to be identified over the course of the test.

Fuel quality issues did occur during testing, and are discussed below, however those issues did not halt testing, and had a minimal affect on boat operation (increased time for cold starting).

Table 5 provides the results of the fuel analyses made on the initial 10,000 gallon batch of fuel, and Table 6 provides the results of analyses conducted after the fuel was reblended to address high butanol levels as discussed in Section 4.5.1. The tables also provide a normal test result for regular gasoline (E0) for comparison.

Table 5. BU16 test results (original fuel batch).

Original Fuel Batch

		Delivery Date >>	6/19/13	7/23/13	8/16/13	10/18/13	11/8/13	11/12/13	1/24/14	3/5/14
		Gallons Delivered >>	750	446.7	425	450		400.1	414	449
		Sampled by >>	GEVO	RDC	RDC	RDC	RDC	RDC	RDC	RDC
		Sampled From >>	DST	DDT	DDT	DDT	DST	DDT	DDT	DDT
		Testing Lab >>	Intertek	Southwest	Southwest	Southwest	Southwest	Southwest	Southwest	Southwest
Oxygenates and Total Oxygen	Regular Gasoline									
Methanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Ethanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Iso-Propanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
n-Propanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
t-Butanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
n-Butanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Iso-Butanol (16.1 (+/- 0.268%)	(2)	Vol. %	15.99	17.50	17.79	18.47	18.68	18.67	19.81	20.22
sec-Butanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
MTBE	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
ETBE	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
DIPE	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
TAME	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
t-Pentanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Oxygenates	(2)	Vol. %	15.99	17.50	17.79	18.47	18.68	18.67	19.81	20.22
Total Oxygen	3.7 % (Ethanol)(3)	Wt. %	3.70	2.74	4.08	4.22	4.24	4.24	4.46	4.62
(Vapor Pressure) RVP	(7-15 psi) (4)	psi	NT	6.67	6.77	6.38	5.32	5.30	4.46	4.04
(Vapor Pressure) DVPE		psi	NT	5.64	6.63	6.25	5.17	5.16	4.31	3.88
(Copper Strip Test) Corrosion	1-4 (5)	rating	NT	1A	1A	1A	1A	1A	1A	1A
(Copper Strip Test) Duration	Test parameters	hours	NT	3	3	3	3	3	3	3
(Copper Strip Test) Temp.	Test parameters	° C	NT	50	50	50	50	50	50	50
Heat of Combustion/Gross	20,000	BTU/lb	NT	NT	18874	NT	NT	NT	18788	NT
Heat of Combustion/Gross	46.52	MJ/kg	NT	NT	43.900	NT	NT	NT	43.700	NT
Heat of Combustion/Gross	11,300	cal/g	NT	NT	10485.3	NT	NT	NT	10437.5	NT
Heat of Combustion/Net		BTU/lb	NT	NT	17644	NT	NT	NT	17578	NT
Heat of Combustion/Net		MJ/kg	NT	NT	41.039	NT	NT	NT	40.888	NT
Heat of Combustion/Net		cal/g	NT	NT	9801.9	NT	NT	NT	9765.8	NT
Research Octane Number (RON)	(6)		NT	95.5	95.4	94.7	95.7	95.6	95.4	96.3
Motor Octane Number (MON)	(6)		NT	85.0	85.1	83.7	84.9	84.9	84.7	85.5
AKI (RON+MON)/2	87,89, or 91-94 (6)			90.3	90.3	89.2	90.3	90.25	90.05	90.9
Unwashed Gum		mg/100 mL	NT	9.0	48.0	536	12	10.5	13	14
Washed Gum	5 (Maximum)(7)	mg/100 mL	NT	1.0	6.0	13.0	2.5	2.5	5.0	<0.5
API Gravity	59.97		NT	55.5	55.1	54.5	53.1	53	51.5	50.6
Specific Gravity	0.739		NT	0.7568	0.7582	0.7608	0.7664	0.7669	0.7732	0.7769
Density at 15°C	710-770	g/L	NT	756.5	757.9	760.6	766.2	766.7	772.9	776.6
V/L Ratio	(97- 176)(8)	Temp. (°F)	NT	154.6	155.5	155.9	165.9	167	>176	>176
Oxidation Stability/Run Time	240 (Minimum)	minutes	NT	1440	1440	1440	1440	1440	1440	1440
Oxidation Stability/Break Pt.		yes/no	NT	No	No	No	Yes	Yes	Break	Break
Oxidation Stability/Break Pt.		minutes	NT	N/A	N/A	N/A	909	908	937	868
Water Content	(9)	ppm/mass %	NT	1539	2783	2835	2512	2524	2593	2319
Sulfur Content	0.0080% (Maximum) (10)	Wt. %	?	NT	0.0035	NT	NT	NT	0.0032	NT
Corrosion Silver Strip	0-4 (11)	rating	?	0	0	0	0	0	0	0
Test	**Limits**	**Units**	NT = not tested		DST = Domestic storage tank			DDT = Domestic delivery truck		

Notes: 1. Values in red represent out of spec test results
2. Regular gasoline can contain a number of different of oxygenates as listed. 10% Ethanol or less is the most common. The oxygenate test results (Less that 0.1% for all except isobuatnol) show isobuatnol is the primary oxygenate.
3. Maximum approved Oxygen concentration approved by EPA with 10 % Ethanol as oxygenate.
4. Normal Range of Vapor Pressure - Varies with the seasons - Lower vapor pressure prevents vapor lock and hot fuel handling problems but can make for hard starting. High values for better cold start performance.
5. Reported on scale of 1-4 with one being the best. Max. 1A = Freshly polished. 1B= Slight tarnish. 4 = worst, severe corrosion. Appears as blackened test coupon.
6. RON always greater than MON and difference indicates sensitivity of gasoline to operating condition changes. The larger the difference the more sensitive. Antiknock Index (AKI) is what is usually posed on pump. AKI is (RON+MON)/2. AKIs vary 87 for regular, 89 for midgrade and 91-94 for premium.
7. Impact of Solvent washed Gums on malfunctions of modern engines is not well established and the current specification limit is historic rather that result of recent correlative study.
8. Gasolines with higher values provide better protection against vapor lock and hot fuel handling problems.
9. Water in solution operates as an inert diluent and will be vaporized in the combustion process. Gasoline blends with low molecular alcohols can dissolve about 0.1 %(1000 ppm) to 0.7 % (7000 ppm) mass percent water under normal conditions.
10. Maximum Sulfur for unleaded gasoline.
11. Reported on scale of 0- 4 . 0= no tarnish, identical to a freshly polished strip, but may have some very light loss of luster.

Table 6. BU16 test results (reblended fuel).

			Reblended Fuel						
		Delivery Date >>	4/25/14	5/15/14	5/21/14	6/5/14	6/24/14	7/3/14	7/3/14
		Gallons Delivered >>	427.2			384.3			442.7
		Sampled by >>	RDC	RDC	GEVO	RDC	GEVO	GEVO	RDC
		Sampled From >>	DDT	DDT	YTT	YTT	DST	DDT	DDT
		Testing Lab >>	Southwest	Southwest	Intertek	Southwest	Intertek	Intertek	Southwest
Oxygenates and Total Oxygen	Regular Gasoline								
Methanol	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
Ethanol	(2)	Vol. %	<0.1	NT	<0.1	<0.1	0.28	<0.1	<0.1
Iso-Propanol	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
n-Propanol	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
t-Butanol	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
n-Butanol	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
Iso-Butanol (16.1 (+/- 0.268%)	(2)	Vol. %	24.35	16.86	16.69	21.23	15.27	18.57	20.46
sec-Butanol	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
MTBE	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
ETBE	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
DIPE	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
TAME	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
t-Pentanol	(2)	Vol. %	<0.1	NT	<0.1	NT	<0.2	<0.1	<0.1
Oxygenates	(2)	Vol. %	24.35	NT	16.69	21.23	15.6	18.57	20.46
Total Oxygen	3.7 % (Ethanol)(3)	Wt. %	5.40	NT	3.8	4.99	3.6	4.2	4.59
(Vapor Pressure) RVP	(7-15 psi) (4)	psi	3.26	5.22	NT	3.07	NT	NT	4.38
(Vapor Pressure) DVPE		psi	3.09	5.07	NT	2.9	NT	NT	4.22
(Copper Strip Test) Corrosion	1-4 (5)	rating	1A	NT	NT	1A	NT	NT	1A
(Copper Strip Test) Duration	Test parameters	hours	3	NT	NT	3	NT	NT	3
(Copper Strip Test) Temp.	Test parameters	° C	50	NT	NT	50	NT	NT	50
Heat of Combustion/Gross	20,000	BTU/lb	18556	NT	NT	NT	NT	NT	18786
Heat of Combustion/Gross	46.52	MJ/kg	43.161	NT	NT	NT	NT	NT	43.696
Heat of Combustion/Gross	11,300	cal/g	10308.9	NT	NT	NT	NT	NT	10436.7
Heat of Combustion/Net		BTU/lb	17374	NT	NT	NT	NT	NT	17594
Heat of Combustion/Net		MJ/kg	40.412	NT	NT	NT	NT	NT	40.924
Heat of Combustion/Net		cal/g	9652.2	NT	NT	NT	NT	NT	9774.4
Research Octane Number (RON)	(6)		96.4	NT	NT	97	NT	NT	97.1
Motor Octane Number (MON)	(6)		85.4	NT	NT	84.9	NT	NT	86.1
AKI (RON+MON)/2	87,89, or 91-94 (6)		90.9	NT	NT	90.95	NT	NT	91.6
Unwashed Gum		mg/100 mL	13.5	29	NT	16	NT	NT	14.5
Washed Gum	5 (Maximum)(7)	mg/100 mL	4.0	5	NT	3.5	NT	NT	4.0
API Gravity	59.97		49.0	52.7	NT	48.4	NT	NT	51.1
Specific Gravity	0.739		0.7840	0.7682	NT	0.7865	NT	NT	0.7749
Density at 15°C	710-770	g/L	783.7	767.9	NT	786.2	NT	NT	774.6
V/L Ratio	(97- 176)(8)	Temp. (°F)	>176	NT	NT	>176	NT	NT	>176
Oxidation Stability/Run Time	240 (Minimum)	minutes	1440	NT	NT	1440	NT	NT	1440
Oxidation Stability/Break Pt.		yes/no	Break	Yes	NT	Break	NT	NT	Break
Oxidation Stability/Break Pt.		minutes	792	665	NT	905	NT	NT	905
Water Content	(9)	ppm/mass %	2862	NT	NT	3105	NT	NT	1906
Sulfur Content	0.0080% (Maximum) (10)	Wt. %	0.0032	NT	NT	NT	NT	NT	0.0033
Corrosion Silver Strip	0-4 (11)	rating	0	NT	NT	0	NT	NT	0
Test	**Limits**	**Units**	NT = not tested				DST = Domestic storage tank		
			DDT = Domestic delivery truck				YTT = Yorktown trailerable tank		

Notes: 1. Values in red represent out of spec test results

2. Regular gasoline can contain a number of different of oxygenates as listed. 10% Ethanol or less is the most common. The oxygenate test results (Less that 0.1% for all except isobuatnol) show isobuatnol is the primary oxygenate.

3. Maximum approved Oxygen concentration approved by EPA with 10 % Ethanol as oxygenate.

4. Normal Range of Vapor Pressure - Varies with the seasons - Lower vapor pressure prevents vapor lock and hot fuel handling problems but can make for hard starting. High values for better cold start performance.

5. Reported on scale of 1-4 with one being the best. Max. 1A = Freshly polished. 1B= Slight tarnish. 4 = worst, severe corrosion. Appears as blackened test coupon.

6. RON always greater than MON and difference indicates sensitivity of gasoline to operating condition changes. The larger the difference the more sensitive. Antiknock Index (AKI) is what is usually posed on pump. AKI is (RON+MON)/2. AKIs vary 87 for regular, 89 for midgrade and 91-94 for premium.

7. Impact of Solvent washed Gums on malfunctions of modern engines is not well established and the current specification limit is historic rather that result of recent correlative study.

8. Gasolines with higher values provide better protection against vapor lock and hot fuel handling problems.

9. Water in solution operates as an inert diluent and will be vaporized in the combustion process. Gasoline blends with low molecular alcohols can dissolve about 0.1 %(1000 ppm) to 0.7 % (7000 ppm) mass percent water under normal conditions.

10. Maximum Sulfur for unleaded gasoline.

11. Reported on scale of 0- 4 . 0= no tarnish, identical to a freshly polished strip, but may have some very light loss of luster.

The RDC required up to 18,600 gallons of BU16 (for the RB-S and for another test boat that is reported separately), based on projected fuel consumption from TRACEN Yorktown estimates. Domestic Fuels blended, stored, and delivered the BU16 fuel to TRACEN Yorktown. Based on the fuel requirement, Domestic dedicated a 10,000 gallon storage tank at their facility and a fuel delivery truck specifically for use on this project. Actual test boat running time was much less than planned, and consumed just under 5,000 gallons of BU16 for the RB-S and the other test boat combined. Eleven BU16 deliveries were made from June 2013 through July of 2014, totaling 4,927.8 gallons. Table 7 provides the delivery dates and quantities delivered.

Table 7. BU16 deliveries.

Delivery Date >>	6/19/13	7/23/13	8/16/13	10/18/13	11/12/13	1/24/14	3/5/14	4/25/14	4/30/14	6/5/14	7/3/14
Gallons Delivered>>	750	446.7	425	450	400.1	414	449	427.2	338.8	384.3	442.7

4.5.1 Biobutanol Percentage

Deliveries were made from the initial 10,000 gallon batch of BU16 over the course of the testing. As the fuel aged during the test period, the biobutanol percentage in the delivered fuel varied. The test team considered butanol levels within 1 percent of the contract requirement of 16.1 percent to be acceptable for test purposes. By the second fuel delivery on 23 July 2013, the butanol level had risen above the acceptable range (17.5 percent), and continued to increase to a maximum of 20 percent, as measured on 5 March 2014. Gevo concluded that the increase in butanol level resulted from vaporization of some of the more volatile compounds in the blend, due to the extended length of time the blended fuel was held in the storage tank. Figure 8 provides biobutanol results for the test period.

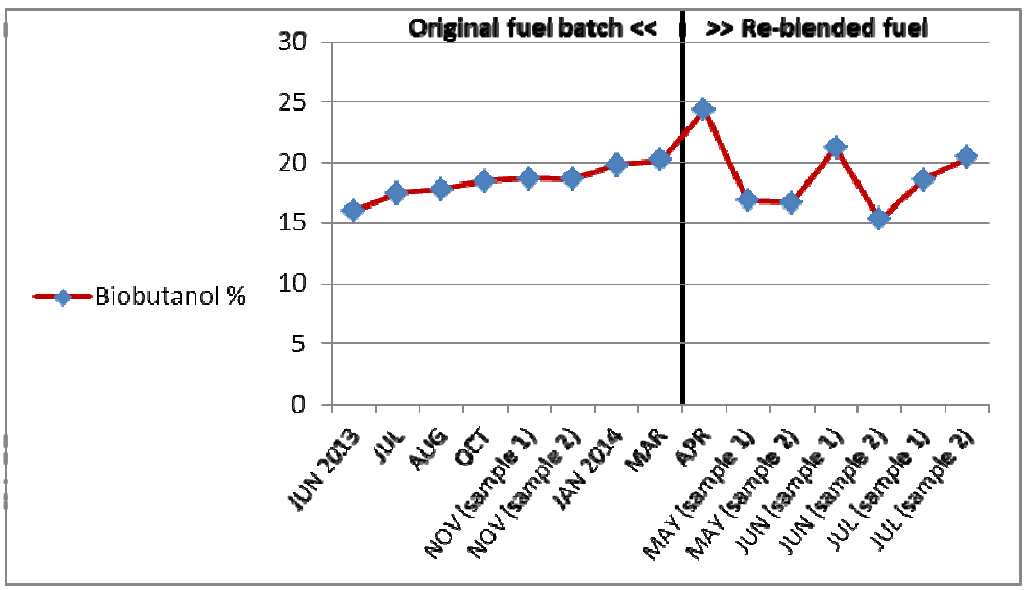

Figure 8. Biobutanol test results.

In January 2014, the test team, in conjunction with ORNL, discussed the rising isobutanol percentage and ways to manage it. Shortly thereafter, the Honda engines began to experience longer cold starting times at ambient temperatures slightly above freezing (see Section 4.5.2). Gevo proposed the following steps to reblend the stored fuel back to 16.1 percent butanol:

1. Test the storage tank to measure the current butanol percentage and calculate a reblend formula.
2. Retrieve the existing fuel located at TRACEN Yorktown in the tanks of the test boat and the trailer-able tank.

3. Purchase eight 55 gallon drums of E0, to produce 2,000 gallons of BU16, based on the existing percentage in the storage tank (the RDC had projected 2,000 gallons was required to complete remaining operational testing).
4. Generate 500 gallon batches of 16 percent isobutanol fuel by blending 100 gallons of E0 with 400 gallons of current fuel for each required delivery (per the formula calculated in item 1 above).

Domestic used the above procedure to reblend BU16 fuel on 24 April 2014 for the final four deliveries, the first of which occurred on 25 April 2014. Test results on the last two deliveries indicated an excessive level of butanol in the blend (20.46 percent in the final delivery); however, the test team determined that the high readings were the result of improper sample collection techniques, and not higher butanol levels. Sampling errors included collecting the sample prior to flushing the tanker delivery line that still contained BU16 from the previous delivery.

4.5.2 Cold Starting Issues

Engine starting problems occurred early in 2014. The boat crew reported difficulty with initial startup on cold days (<35° F), and occasionally the engines completely failed to start. After the engines were started and operated for 5-10 minutes, they performed normally. At the time, fuel sample analysis showed isobutanol levels between 20 and 24 percent, and the fuel was being drawn from a tank blended with summer gasoline 7 or 8 months earlier.

Summer gasoline is required during the summer ozone season (June 1 to September 15) by EPA regulations, to reduce evaporative emissions from gasoline that contribute to ground-level ozone and diminish the effects of ozone-related health problems. This is done by reducing the volatility of the gasoline mixture. Volatility is the property of a liquid fuel that defines its evaporation characteristics, and is represented by Reid vapor pressure (RVP), a common measure of and generic term for gasoline volatility.

As previously noted, Gevo determined that the percentage of isobutanol increased due to evaporation of the more volatile components, increasing the butanol level well above 16.1 percent. The increase in butanol corresponded with a decreasing RVP. RVP decreased from 6.67 psi when first tested from the 23 July 2013 delivery to a low of 3.26 psi on 25 April 2014 (the standard for regular gasoline is 7-15 psi). Figure 9 provides RVP results for the test period.

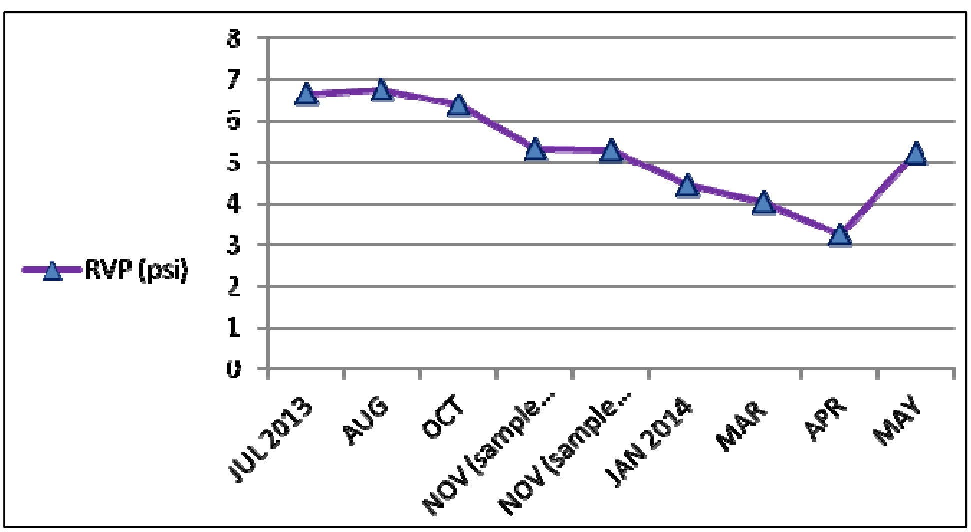

Figure 9. Reid vapor pressure test results.

Once the fuel was reblended with E0 and the isobutanol was brought within specification, no additional starting issues were experienced. The test team was not able to determine whether the problems were resolved by reblending, by warmer ambient temperatures, or both. The cold starting issues were not attributable to a performance issue with the Honda engines. In their interim report (6APPENDIX C), Honda assessed cold startability at -15° C, and concluded:

> “When the mixing ratio of butanol is increased without adjusting the RVP, the RVP drops and oxygen content in the fuel increases, therefore the starting time tends to increase due to the effect of the leaner air-fuel mixture at start.”

As noted in Section 5.1.4, the test team considers it likely that the fuel quality issues experienced during testing would not occur in a commercially available supply of BU16.

4.5.3 Red Color and Particles in the Fuel

During the 23 July 2013 delivery, the Domestic delivery driver noticed a red tint to the fuel. Gevo determined that the red tint was coming from the truck’s fuel hose. A red dye is used to tint off-road diesel fuels, such as marine diesel. Gevo explained that after years of use, the fuel tank hose had absorbed the dye, and subsequently the dye leached out to color the BU16 upon delivery. To avoid this practice in future deliveries, Domestic instituted a process to flush roughly 15 gallons of fuel (the estimated capacity of the fuel hose) through the hose before filling the trailerable tank at Yorktown.

On the same 23 July delivery, TRACEN Yorktown personnel reported particles in the fuel, and Gevo determined that the hose from the delivery truck caused this issue as well. The original hose was a braided hose made of nitrile synthetic rubber, with an outer coating of synthetic rubber. Domestic purchased a new hose determined to be compatible with BU16, and installed it on the tank truck on 2 August 2014. No other issues with color or particles were reported after the new hose was installed.

4.5.4 Washed/Unwashed Gum

After the delivery of fuel on 23 July 2013, sample test results for washed gum reported 6 mg/100mL, exceeding the ASTM D4814 limit of 5 mg/100mL. The unwashed gum content (48 mg/100mL) did not exceed the standard, but showed a marked increase from the sample taken at the first delivery on 19 June (9.0 mg/100mL). The RDC was concerned by the increase, since the two samples came from the same 10,000 gallon batch of fuel blended at the start of testing. Gevo responded to this concern indicating that given their current data, they did not believe that the unwashed gum content would change further, and this anomalous test result was due to an initial residual of fuel in the truck.

After the fourth delivery of fuel on 18 October 2013, the levels of washed and unwashed gum were relatively high (no standard for unwashed gum). Upon investigation, Gevo determined that the fuel delivery truck and its piping were responsible for the contaminated fuel. The truck had been delivering diesel fuel for nearly twenty years, and Gevo indicated that despite a thorough cleaning, residue had contaminated the BU16 and caused the high readings. Gevo initially proposed to use tote tanks to deliver the fuel, taking the tank truck out of the loop, or to use a delivery truck that had only delivered gasoline. Due to state law restrictions on transporting fuel via tote tanks, Gevo decided to use a gasoline truck for future deliveries. As further assurance, the truck was emptied, air dried and then flushed before any more deliveries were made. Problems with washed/unwashed gums did not reoccur on subsequent deliveries.

4.5.5 Crew Feedback

In addition to the quantitative data from the data collection system, the test team captured observations from the RB-S crew at TRACEN Yorktown during periodic visits. These visits also provided an opportunity to retrieve data, ensure the instrumentation was working properly and test protocols were being followed, and perform a visual inspection of the engines and exposed fuel systems. To assist in obtaining the most useful crew data, the test team provided training prior to the start of testing, including the following topics:

- Project background.
- Project goals; specifically for the biobutanol testing.
- Overview of biobutanol fuel; how it is made, advantages, disadvantages, and the Material Safety Data Sheet (MSDS).
- Differences between gasoline fuel and biobutanol fuel including the effects of temperature.
- Safety-related and health issues including safety regulations concerning exposure to biobutanol; i.e., skin contact, ingestion, etc.
- Observations of potential changes to maintenance requirements.
- Changes in Federal and State regulations with regards to reporting of spills, etc.
- Changes in fuel logistics; i.e., biobutanol delivery/storage issues.
- Use/monitoring of data acquisition system.

During the visits, the test team asked the following questions:

1. <u>Have you noticed any difference in boat performance between E0 and BU16</u>? (The test team prompted the crew by asking about specifics such as differences in acceleration, throttle response etc.). Over a year of testing and more than a dozen different crewmembers, the consensus was that there was no difference, with the exception of the cold starting problems noted in Section 4.5.2. As indicated above, cold starting issues were experienced only when fuel analysis showed the butanol percentage to be significantly higher than Honda had specified for proper engine operation from their testing.
2. <u>If you were not told what fuel you were using, would you be able to tell whether it was E0 or BU16?</u> This was asked in the context of a well-running engine and focused on performance. The test team was looking for small nuances of the impact of BU16, such as "the engines seemed sluggish" or "they don't seem as fast" etc. All of the responses indicated there was no difference in performance detected.
3. <u>Have there been any maintenance events with the BU16 that are not encountered with standard E10 fuels?</u> There were no BU16-related maintenance issues.
4. <u>Do you see any reason why BU16 could not be used as an operational fuel (assuming the logistics of delivery and storage are solved)?</u> Again, concerns were voiced only over cold starting issues, which occurred with fuel that was out of specification.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

5.1.1 Overall Result

Based on the testing in this study, BU16 appears to be an acceptable alternative fuel for E10 gasoline, for the engines tested and within the environmental conditions experienced. The impact of BU16 on boat performance and maintenance was no different than when using E10. One potentially desirable property of isobutanol when compared to ethanol is that if the fuel is exposed to a sufficient amount of water to form a

2-phase mixture, ethanol primarily favors the aqueous phase whereas the isobutanol favors the non-aqueous phase. This could offer a significant benefit in the marine environment, where engines are constantly exposed to water. Issues that need further study include the rising levels of butanol noted during storage and materials compatibility in the fuel distribution infrastructure.

5.1.2 Performance

Based on test data and crew observations, the test team and RB-S coxswains and crewmembers perceived no performance difference when operating on BU16 fuel, compared to E10. RB-S performance was no different whether the fuel was E10, BU16, or whether both fuels were mixed together. The cold weather starting problems were caused by aged fuel.

5.1.3 Maintenance

RB-S crewmembers and maintenance personnel detected no effect on maintenance between operating on E10 or BU16. In addition, after testing for materials compatibility, and visually examining engine components following bench testing, Honda detected no difference between the effects of E10 and BU16.

5.1.4 Fuel Quality and Logistics

Although the logistics of fuel distribution, storage and handling was not the focus of this study, a number of issues were noted. Because biobutanol is developmental, many aspects listed below that support a commercially available fuel supply do not currently exist for BU16. The test team assumes that normal market processes would resolve many of the issues, such as storage, price, distribution, and quality.

- Availability: extremely low quantities produced.
- Competition: one U.S. source at this time (Gevo) and one in development (Butamax Advanced Biofuels, LLC).
- Price: unknown, although assumed to be competitive with gasoline to be commercially viable.
- Distribution network: could use existing gasoline distribution network if materials compatibility is confirmed.

The logistics required for this operational test impacted the outcome. A large quantity single batch of blended BU16 fuel was required to be mixed for the testing due to economic considerations. The test fuel was blended using summer base gasoline with a low RVP. The test team believes that the high butanol/low RVP fuel was a result of using summer base gasoline and long storage times. If a robust, fresh supply of fuel is available, these issues could be avoided.

5.1.5 Emissions

Based on Honda's emission testing, the test team considered the emissions using BU16 or E10 to be relatively similar. Honda concluded that for the engines tested:

- BU16 met exhaust emission regulations.
- Both emissions and specific fuel consumption (SFC) using BU16 were equivalent to the levels measured with E10 gasoline.
- Blends as high as 24% butanol can still meet emission regulations.

An increase in the renewable component of the fuel blend (to 24 percent) would reduce emissions when compared to E10, offering a potential advantage for biobutanol.

5.2 Recommendations

5.2.1 Cold Weather Testing

Ambient temperature ranged between 24 and 99 degrees F during the test period. Cold weather testing should be conducted in a location where severe cold weather will commonly be experienced in the winter months, such as New England, Alaska, or in the Great Lakes prior to the onset of ice.

5.2.2 Butanol Storage

The high percentages of butanol in the test fuel experienced during the operational testing should be investigated further. The manufacturers, suppliers and users of biobutanol will need to verify that the increase in butanol percentage noted during this testing does not occur during normal storage conditions. The USCG should continue to monitor this issue to confirm that it does not reoccur.

5.2.3 Infrastructure Materials Compatibility

Materials compatibility of the test engines were verified by Honda prior to the start of the operational test. Although not part of the scope of this test, existing distribution infrastructure materials compatibility with BU16 needs to be confirmed as well. The current suppliers of biobutanol (GEVO, Butamax) have done extensive materials testing through independent laboratories on existing gasoline distribution infrastructure components. The USCG should monitor these results to confirm that the existing USCG infrastructure is compatible with BU16.

5.2.4 Long Term Commercial Viability

This was a focused study that examined the performance of biobutanol as an engine fuel using E10 as the reference on the particular test engines. The test team found that BU16 is a suitable drop-in replacement for E10. Since biobutanol has not yet come to market, aspects of supplying BU16 for this test affected its outcome. Once the fuel is commercially available; its further evaluation and use are recommended.

We recommend that the Coast Guard undertake some simple measures to position itself for the future availability of this fuel.

- Continue to monitor the commercial production capability of biobutanol producers as they bring their product to market.
- Once commercial availability has been established, consider adding biobutanol fuel capability as an added requirement for future outboard engine procurements.
- Ensure issues noted in this report (butanol storage, infrastructure compatibility) are satisfactorily addressed.

6 REFERENCES

1. Department of Homeland Security. (2011). Department of Homeland Security (DHS) Strategic Sustainability Performance Plan. Retrieved from http://www.dhs.gov/sites/default/files/publications/dhs-2011-strategic-sustainability-performance-plan.pdf

2. Kass, M., Janke, C., Pawel, S., Thomson, J., Meyer, H., & Theiss, T. (2013). Compatibility Study for Plastic, Elastomeric, and Metallic Fueling Infrastructure Materials Exposed to Aggressive Formulations of Isobutanol-blended Gasoline. ORNL/TM-2013/243, August 2013. Retrieved from http://info.ornl.gov/sites/publications/Files/Pub44488.pdf

3. Kass, M., Janke, C., Theiss, T., Pawel, S., et al. (2014). Compatibility Assessment of Plastic Infrastructure Materials to Test Fuels Representing Gasoline Blends Containing Ethanol and Isobutanol. *SAE Int. J. Fuels Lubr. 7(2):* 457-470. doi:10.4271/2014-01-1465.

4. Kass, M., Theiss, T., Pawel, S., Baustian, J., et al. (2014). Compatibility Assessment of Elastomer Materials to Test Fuels Representing Gasoline Blends Containing Ethanol and Isobutanol. *SAE Int. J. Fuels Lubr. 7(2):* 445-456. doi:10.4271/2014-01-1462.

5. Remley, B., Nastase, K., Pembrooke, P., Sprague, M., Turner, C., & Gynther, J. (2011). Report on alternative fuel options for Coast Guard vessels. RDC UDI #1116.

6. United States Coast Guard and Honda R&D Americas Joint Research. (2013). *Compatibility of Outboard Engines with Butanol-mixed Alternative Fuel Performance/Function Tests [Interim Report]*. (Publication No. 130401905S)

APPENDIX A. ALTERNATIVE FUEL EVALUATION MATRIX

Table A-1. Alternative fuel evaluation matrix.

								Candidate Gasoline Alternative Fuels											
								Gasoline (E10)		CNG (3)		LNG (3)		Biobutanol		Ethanol (E85)		Biomass-to-Liquids	
	Category	Attribute		Importance Weighting Factor (WF) (2)	Attribute Rankings (1)	High Score	Low Score	WF	WF*Imp Rating	WF	WF*Imp Rating	WF	WF*Imp Rating	WF	WF*Imp Rating	WF	WF*Imp Rating	WF	WF*Imp Rating
1	Economic Factors	Fuel Cost	Alt Fuel Cost on a per gallon or gallon equivalent basis.	3	1=Significant Increase over baseline 2=Moderate increase over baseline 3=Same cost or less than baseline	9	3	3	9	3	9	3	9	2	6	2	6	1	3
2	Economic Factors	Modification Cost	Cost associated with modifying the ACTD for use of the proposed Alternative fuel.	2	1=Significant, > $500K 2=Mid Range, $100K - $500K 3= Moderate, <$100K	6	2	3	6	2	4	2	4	3	6	2	4	3	6
3	Maturity	Availability	Alternative Fuel available with distribution support for 2011-2012 ACTD	3	1= Experimental (Laboratory) with little or no support. 2= Prototype Development with some support. 3= Mature (Commercially Available) and well supported.	9	3	3	9	3	9	3	9	2	6	3	9	2	6
4	Maturity	OEM Approval	Engine OEM Approval for fuel	2	1=No 2=Yes	4	2	2	4	1	2	1	2	1	2	2	4	1	2
5	Maturity	Marine Applications	Marine Applications	2	1= No Known Applications 2= Experimental Applications Only 3= In use by Marine Industry	6	2	2	6	3	6	3	6	1	2	1	2	1	2
6	Maturity	Transit Applications	Transit Applications	2	1= No Known Applications 2= Experimental Applications Only 3= In use by Transit Industry	6	2	2	4	3	6	3	6	2	4	3	6	1	2
7	Maturity	Vendors	Vendors:	3	1=No vendors (Laboratory Only) 2=Few vendors 3=Ample vendors	9	3	3	9	3	9	2	6	2	6	3	9	2	6
8	Performance	Carbon Footprint	Reduction in Carbon Footprint (GHG) from Baseline Fuel (Regular Gasoline)	3	1=No reduction in Carbon Footprint 2= moderate reduction in Carbon Footprint (≤ 50%) 3 =Substantial reduction in Carbon Footprint (≥ 50%)	9	3	2	6	2	6	2	6	2	6	2	6	3	9
9	Performance	Engine Performance	Effect on ACTD Engine HP	3	1=Degraded 2=No effect 3=Improved	9	3	2	6	1	3	2	6	2	6	2	6	2	6
10	Performance	Fuel Consumption	Specific Fuel Consumption: (SFC)	3	1=Increase 2=No effect 3=Decrease	9	3	1	3	1	3	1	3	1	3	1	3	2	6
11	Performance	Engine Exhaust Emissions	Impact on Engine Exhaust Emissions (CACs- NOx, SOx, HC, CO, and PM)	2	1=Little to no Reduction 2=Some Reduction 3=Significant Reduction	6	2	2	4	3	6	3	6	2	4	2	4	3	6
12	Performance	Endurance	Endurance (Range)	2	1= Use of Fuel will result in significant reduction of ACTD endurance 2= Use of Fuel will result in moderate reduction of ACTD endurance 3= Use of Fuel will result in little or no reduction of ACTD endurance	6	1	3	6	1	2	1	2	3	6	1	2	3	6
13	Physical	Engine Modifications	Engine Modifications Required	2	1=Major modifications required to engine. 2=Minor modifications required 3=No modifications required	6	2	3	6	1	2	1	2	3	6	1	2	2	4
14	Physical	Boat Modifications	Boat Modifications Required	2	1=Major modifications required. 2=Minor modifications required 3=No modifications required	6	2	3	6	1	2	1	2	3	6	2	4	2	4
15	Physical	Boat Weight	Weight effect on ACTD Boat	3	1= Significant Increase 2=Some Increase 3= Decrease or no Increase	9	3	3	9	1	3	1	3	2	6	3	9	3	9
16	Physical	Fuel Volume (capacity)	Volume Effect on ACTD	3	1= Significant Increase 2=Some Increase 3= Decrease or no Increase	9	3	3	9	1	3	1	3	3	9	3	9	3	9
17	Physical	Fuel Storage	Special Fuel Storage	3	1= Extensive requirements 2= Some requirements 3= No special requirements	9	2	3	9	1	3	1	3	3	9	2	6	3	6
18	Reliability	Reliability	Reliability/Durability	2	1= Degraded 2= Little or no effect 3=Improved	6	2	2	4	2	4	2	4	2	4	1	2	2	4

Table A-1. Alternative fuel evaluation matrix (cont.).

	Category	Attribute		Importance Weighting Factor (WF) (2)	Attribute Rankings (1)	High Score	Low Score	Candidate Gasoline Alternative Fuels: Gasoline (E10) WF	Gasoline (E10) WF*Imp Rating	CNG (3) WF	CNG (3) WF*Imp Rating	LNG (3) WF	LNG (3) WF*Imp Rating	Biobutanol WF	Biobutanol WF*Imp Rating	Ethanol (E85) WF	Ethanol (E85) WF*Imp Rating	Biomass-to-Liquids WF	Biomass-to-Liquids WF*Imp Rating
19	Safety	Toxicity	Toxic Properties: Causes injury or death if inhaled, ingested, or contacted.	3	1=Highly Toxic	9	3												
					2=Somewhat Toxic			2	6										
					3=Non-Toxic					3	9	3	9	3	9	3	9	3	9
20	Safety	Explosive	Explosive Properties	3	1=Highly Explosive	9	3	1	3	1	3								
					2=Somewhat explosive							2	6	2	6	2	6	2	6
					3=Non-explosive														
21	Safety	Flash Point	Flash point as compared to the flash point of the baseline fuel (Regular Gasoline).	3	1= Less then the baseline fuel	9	3			1	3	1	3						
					2= The same as the baseline fuel.			2	6										
					3= Greater then the baseline fuel.									3	9	3	9	3	9
22	Logistics	Regulations	Governing Regulations	2	1=Extensive Regulations	6	2	1	2	1	2	1	2			1	2		
					2=Few Regulations									2	4				
					3=No regulations													3	6
23	Logistics	Specifications	Fuel Specification	3	1=Fuel not produced to ASTM or equivalent Fuel Std.	9	3											1	3
					2=Fuel not produced to ASTM or equivalent Fuel Std but certified.									2	6				
					3=Fuel is produced to ASTM or Equivalent Gasoline Fuel Std			3	9	3	9	3	9			3	9		
24	Lessons Learned	Benefits	Benefits	2	1= Few to No Benefits	6	2												
					2= Some Benefits			2	4							2	4		
					3= Major Benefits					3	6	3	6	3	6			3	6
25	Lessons Learned	Drawbacks	Drawbacks	2	1= Major Drawbacks	6	2					1	2			1	2		
					2= Some Drawbacks but not of major consequence.			2	4	2	4			2	4			2	4
					3= No drawbacks														
					Totals	187	61	58	149	47	118	47	119	56	141	51	134	56	139
					Scale of 1-10	10	1	NA	8.0	NA	6.3	NA	6.4	NA	7.5	NA	7.2	NA	7.4

Notes:
(1) If information is not available for an attribute for whatever reason (For example The technology is in the developmental state and certain parameters have not been established) then a zero is assigned in the Matrix.
(2) Attributes Importance Weighting Factors: 1= Important, 2 = Moderately Important, 3 = Very Important
(3) Includes bi-fuel systems where gasoline and natural gas are used in combination to exploit the advantages of both fuels.

APPENDIX B. BUTANOL/GASOLINE TEST PLAN

The Butanol/Gasoline Test Plan is provided as a separate electronic document to comply with file size limitation requirements.

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APPENDIX C. DRAFT RB-S TIME COMPLIANCE TECHNICAL ORDER (TCTO)

Draft Gasoline Time Compliance Technical Order (TCTO):

Data for Input to TCTO Phase 1 Form (Section 1)

Contract No. HSCG32-10-D-R00021
Task Order HSCG32-11-J-300018, Deliverable 4
Project 4103 – Operational Testing of Alternative Fuels

31 January 2012

1. Case File #: [leave blank]
2. TCTO #: [leave blank]
3. Type: RB-S
4. Title: Modification for Alternative Fuel Testing (Biobutanol) on CG-25750 (Yorktown, VA)
5. Submitted by: Coast Guard Research & Development Center
6. Submission Date: [leave blank]
7. Desired Installation Date: 3 October 2012
8. Requirement/Description: See Table 1, which lists changes recommended to CG-25750 prior to commencement of biobutanol (BU16) testing. Table 2 contains cost details for all recommended items.

Table 1. Recommended Changes to RB-S CG-25750 to Support BU16 Testing.

Task	Description	Rec.	May Need to be done	Comments
1	**Fuel Tanks**			
a	Compatibility		**X**	In general, butanol has not been found to have adverse effects on any materials typically found in gasoline fuel systems. Aluminum, such as the fuel tank on the RB-S, has not been tested yet; however, Butamax is in the process of doing materials testing on samples provided by the manufacturer with results expected summer 2012.
2	**Fuel System Modifications**			
a	Replace fuel system flex hoses, with BU16-compatible parts and components.		**X**	The current nitrile and aluminum hoses are compatible with E85 gasoline. They are probably OK with BU16 but waiting for feedback from Butamax and Gevo.
b	Replace metallic fuel line fittings and components that are not compatible with the BU16 fuel.		**X**	There are several aluminum fuel line fittings that may be an issue: see comments above with regards to aluminum.
c	Modify or change out fuel filters/water separators.		**X**	The RACOR-Parker fuel filter manifold is cast aluminum and the filter/water separator has an aluminum can: see comments above about aluminum. The fuel filter has a plastic bowl and buna-N gasket which are compatible with E10 but have not been confirmed to be compatible with BU16 yet.
3	**Instrumentation**			
a	FloScan fuel flow meter		**X**	The FloScan meters need to be confirmed to be compatible with the Honda engines, and BU16. The body of the FloScan transducer is either zinc or aluminum; this needs to be determined. Zinc should be replaced; aluminum may be OK (see comment 1a above).
b	Data recorder	**X**		Use output from engine ECUs to monitor engine horsepower and other parameters. A data recorder with an NMEA2000 interface must be added to the engines to automatically log the data to a flash card for monthly retrieval.
c	Nav box	**X**		A data collection (nav) box will be installed in a location that is determined to not interfere with operational requirements. This nav box will have a GPS receiver (L1 DGPS or WAAS), heading/pitch/roll sensors, a data collection computer (such as the Moxa UC-8418 embedded computer) for long-term data

Table 1. Recommended Changes to RB-S CG-25750 to Support BU16 Testing.

Task	Description	Rec.	May Need to be done	Comments
				collection and a weather station (such as Maretron WSO100) installed in it. The nav box will require 24 VDC and the mounting of the GPS and weather station antennas.
4	**Engine Modifications**			
a	Change out metallic and non-metallic parts that are not BU16-compatible based on results of Honda and Mercury material testing.		X	Modify engines as recommended by Honda. Waiting for results of their testing, which will be available on 1 August 2012.
5	**Miscellaneous**			
a	Provide extra fuel filter elements.		X	If the existing fuel filters are NOT compatible with BU16 and specialized fuel filters are needed, then extras need to be provided to the unit. Waiting for feedback from Butamax and Gevo on fuel filter issues.
b	Restore RB-S to pre-demonstration configuration.		X	Return test boat to the standard configuration.

Table 2. Cost Details for each TCTO Item.

TCTO Line #	Item/Service	Suggested Manufacturer	Suggested Part Number	Qty	Cost Each	Sub-Total	Install Cost	Total Cost	Notes
1a	Fuel tank			1					**Note 1:** A requirement for these potential items will be determined upon receipt of results of material testing and costs estimated at that time.
2a	Fuel system hoses			1					
2b	Fuel fittings			1					
2c	Fuel filter/water separators			1					
3a	FloScan			1					
3b	NMEA data recorder	Maretron	VDR100	1	$1,050	$1,050	$0	**$1,050**	**NMEA subtotal estimate** (to be installed by USCG or test team)
3c	Nav box: Weather station/GPS	New Mountain	NM100 Weather Station	1	$1,400	$1,400	$0	$1,400	
	Nav box: Data collection computer	Moxa	IA261-I/262-I Series	1	$1,250	$1,250	$0	$1,250	
	Nav box: Inertia Measurement Unit (IMU)	Honeywell	HMR2300	1	$850	$850	$0	$850	
	Nav box: Enclosure, power supply, miscellaneous cables	SKB, miscellaneous	Miscellaneous	1	$800	$800	$0	$800	
			Subtotal	1	$4,300	$4,300	$0	**$4,300**	**Nav box subtotal estimate** (to be installed by test team; estimated 4 hrs)
4a	Incompatible engine parts								See Note 1 above
5a	Extra fuel filters			30					See Note 1 above
								$5,350	**Total estimate for RB-S**

APPENDIX D. HONDA PERFORMANCE/FUNCTION TEST REPORT ORDER (TCTO)

USCG & HRA Joint Research
Compatibility of Outboard Engines with
Butanol-mixed Alternative Fuel
Performance/Function Tests **[Interim Report]**

May/10/2013

Honda R&D Co., Ltd. Power Products R&D Center

Honda R&D Americas, Inc. Florida

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130401905S

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1. Background

Ethanol based fuels in the United States have been reported cause problems due to the tendency of ethanol to mix with water. As such, the validity of ethanol as an alternative fuel is questionable.
Therefore, the U.S. Coast Guard Research and Development Center and Honda R&D Americas, Inc. are conducting joint research into the compatibility of butanol-mixed fuel with outboard engines by focusing on potential use of butanol as an alternative fuel according to the U.S. Executive Order that requires government agencies to investigate long-term strategies for reducing green house gases.

2. Purpose

The purpose of this project is to check the degree to which engine performance, component function and durability/reliability of multiport fuel injection outboard engines that are currently available on the market would be influenced when a butanol-mixed fuel having a lower hygroscopic property is used, and shed light on the allowable mixing ratio of butanol.
Multiport fuel injection is hereinafter referred to as “MFI.”
As shown in Fig. 1, this project consists of three elements, namely “Engine Performance Tests,” “Component Function Tests” and “Durability/Reliability Tests”. This interim report outlines the results of these tests.
Durability/reliability tests are conducted on MFI outboard engines currently available on the market based on the allowable mixing ratio of butanol, as determined by the engine performance/component function tests conducted.

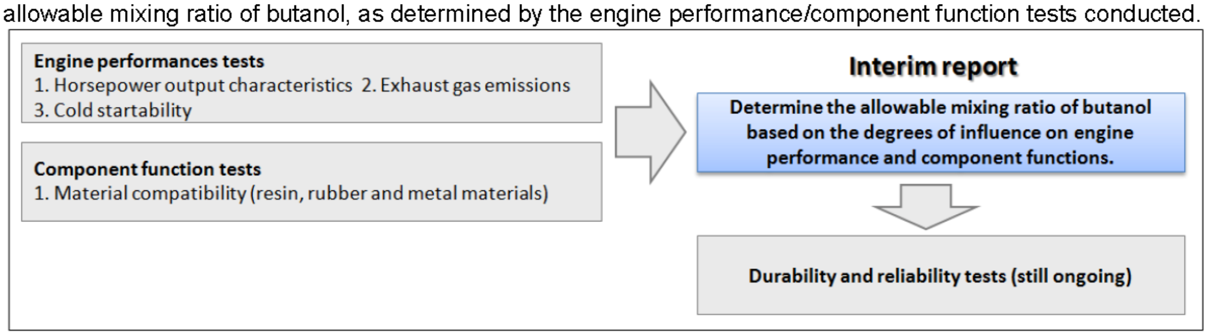

Fig. 1: <u>Outline of this interim report</u>

3. Items Checked for Determination of Allowable Mixing Ratio for Outboard Engines

The engine performance items and component functions shown in Fig. 2, which are likely affected when butanol is mixed given the different fuel characteristics of gasoline, ethanol and butanol, were checked.

1. Engine performance tests: Output characteristics, exhaust gas emission characteristics, cold startability
2. Component function tests: Verification of allowable mixing ratio of butanol for fuel-supply system parts as compared to gasoline

Item	Gasoline		Butanol		Ethanol
Energy density [%]	100	>	84	>	66
Oxygen content[wt %]	0	<	21.6	<	34.7
Stoichiometrical air-fuel mixture ratio	14.6	>	11.2	>	9
Pump Octane [(RON+MON) / 2]	86	<	98	<	102
Reid vapor pressure RVP [kPa]	44 - 78	>	3.4	<	16
Hygroscopicity property	None	<	Low	<	High
Alcohol content	Not contained	>	Contained	=	Contained

Items checked for determination of allowable mixing ratio	
Engine performance tests	･Horsepower output characteristics ･Exhaust gas emission characteristics ･Cold startability
Component function tests	･Corrosion of metal components due to water
	･Corrosion of metal components due to alcohol ･Swelling of resin and rubber components due to alcohol.

☆Engine performance/component function tests were conducted using iso-butanol.

Fig. 2: <u>Comparison of Fuel Characteristics and Items Checked for Determination of Allowable Mixing Ratio</u>

4. Engine Performance Test Results

4.1. Summary of engine performance tests

Test results are shown in Table 1.

The allowable mixing ratio of butanol for MFI outboard engines currently available on the market is 16.5 percent by volume or less, due to the cold startability at -15ºC as a restrictive factor.

Item			Allowable mixing ratio of butanol
Engine performance	Horsepower output characteristics		0～50 vol%
	Exhaust gas emission characteristics		0～(50 vol%)*
	Cold startability	-15℃	0～ 16.5 vol% ← **This restricts the allowable mixing ratio.**
		0℃	0～25 vol%

***Emissions at a butanol mixing ratio of 25 percent by volume or more are provided for reference purposes only.**

Table 1: Engine Performance Tests and Impact on Allowable Mixing Ratio

4.1.1. Horsepower output characteristics

The allowable mixing ratio that ensures horsepower output equivalent to when gasoline (E0) is used, is 50 percent by volume or less.

4.1.2. Exhaust gas emission characteristics

4.1.2.1. The allowable mixing ratio that satisfies the exhaust gas emission regulation values is assumed as 50 percent by volume or less. Note that emissions at a butanol mixing ratio of 25 percent by volume or more are provided for reference purposes only because they were not measured in compliance with the measurement method specified in 40 CFR, Part 1065, Subpart I.

4.1.2.2. When the mixing ratio of butanol is 16.5 percent by volume or less, both emissions and specific fuel consumption (SFC) are equivalent to the levels measured with E10 gasoline.

4.1.3. Cold startability (Ambient temperature: -15°C and 0°C)

Cold startability is determined by the startability at -15°C when the RVP is adjusted to a level equivalent to the RVPs of fuels currently available on the market (E0 gasoline and E10 gasoline); and the allowable mixing ratio of butanol that ensures startability equivalent to when E10 gasoline is used is 16.5 percent by volume.

4.2. Engine performance test conditions

Table 2 lists the horsepower output characteristics, exhaust gas emission characteristics and cold startability test conditions.

Test item	Test unit	Test equipment	Test fuel	Test method
Horsepower output Characteristics	BF150 M/P unit (2011MY)	・Eddy Current Dynamometer :MEIDENSHA Co., Ltd TYPE：PEW-DID ・Mass-burette type fuel flow meter :ONO SOKKI Co., Ltd Gravity Flow Sensor TYPE：FX-1130 Flow Meter TYPE：FM2500 ・Motor Exhaust Gas Analyzer :HORIBA Co., Ltd. TYPE：MEXA-7100 Analysis method CO/CO2 ：NDIR THC：FID , NOx：CLD	a. Gasoline : Regular（Pump Octane 86.5） b. E10 Base Gasoline : Regular（Pump Octane 86.5） Ethanol: Derived from plants Mixing ratio : 10 vol% c. Butanol-mixed fuel Base Gasoline：Regular（Pump Octane 86.5） Butanol : Derived from petroleum Mixing ratio :10,16.5,20,50,75 vol%	Conforming to SAE-J1228 / ISO 8665
Exhaust gas Emission characteristics			a. Gasoline : Indolene（Pump Octane 91.5） b. E10 Base Gasoline : Indolene（Pump Octane 91.5） Ethanol: Derived from plants Mixing ratio : 10 vol% c. Butanol-mixed fuel Base Gasoline : Indolene（Pump Octane 91.5） Butanol : Derived from petroleum Mixing ratio : 10,16.5,20,50,75 vol%	a. Conforming to 40 CFR 91 Subpart B and SAE J1228 / ISO 8665 b. Emissions at a butanol mixing ratio of 25 percent by volume or more are provided for reference purposes only because they were not measured in compliance with the exhaust gas emission measurement method specified in 40 CFR, Part 1065, Subpart 1.
Cold startability -15℃／0℃	BF225 M/P unit (2011MY)	・Low-temperature test chamber	a. Gasoline : ASTM class B RVP b. E10 Base Gasoline : ASTM class A RVP Ethanol: Derived from plants Mixing ratio : 10vol%(ASTM class B RVP) c. Butanol-mixed fuel [Low-RVP] Base Gasoline : ASTM class A RVP Butanol : Derived from petroleum Mixing ratio : 10,16.5,20,50 vol% d. Butanol-mixed fuel [High-RVP] Base Gasoline : ASTM class D RVP Butanol : Derived from petroleum Mixing ratio : 16.5,30,50 vol%	

Table 2: Engine Performance Test Conditions

4.3. Horsepower output characteristics

4.3.1. Purpose

To research the allowable mixing ratio of butanol, verify how butanol-mixed gasoline affects maximum horsepower output.

4.3.2. Conditions

Measure horsepower output with throttle at wide-open (WOT) and operating at the maximum engine speed of 6000rpm as recommended for the BF150, based on the engine performance test conditions in Table 2.

4.3.3. Judgment criteria

An allowable mixing ratio of butanol is one that produces horsepower equivalent to that of gasoline (E0).

4.3.4. Result

In terms of horsepower output characteristics, the allowable mixing ratio of butanol is 50 percent by volume or less.

Refer to Fig. 3 for the explanations of the statements provided below.

4.3.4.1. At up to a 50 percent mix ratio of butanol, horsepower output is equivalent to that produced by gasoline (E0), as shown in the Output graph and Torque graph.

4.3.4.2. When the mix ratio of butanol is more than 50 percent by volume, the output tends to drop as the mixing ratio increases, as shown in the Output graph and Torque graph.
The drop in output is caused by the following factors relating to fuel properties as shown in the NHV vs. λ graph:

1. Drop in the heating value of fuel (NHV, or Net Heating Value)
2. Change of λ (rate of excess air) toward the leaner side

4.3.4.3. When the mix ratio of butanol is 75 percent by volume, the brake specific fuel consumption (BSFC) increases by 5.7% due to the drop in output, as shown in the Output graph, Torque graph and BSFC graph.

4.3.4.4. When the mix ratio of butanol is 50 percent by volume or less, the air-fuel ratio is leaner at maximum horsepower output, due to the effects of fuel properties as shown in the λ graph and CO graph, and the horsepower output tends to rise slightly as a result, as shown in the Output graph and Torque graph. Also, as shown in the Pump Octane graph, the octane value of fuel rises as the mix ratio increases and thus knocking does not occur.

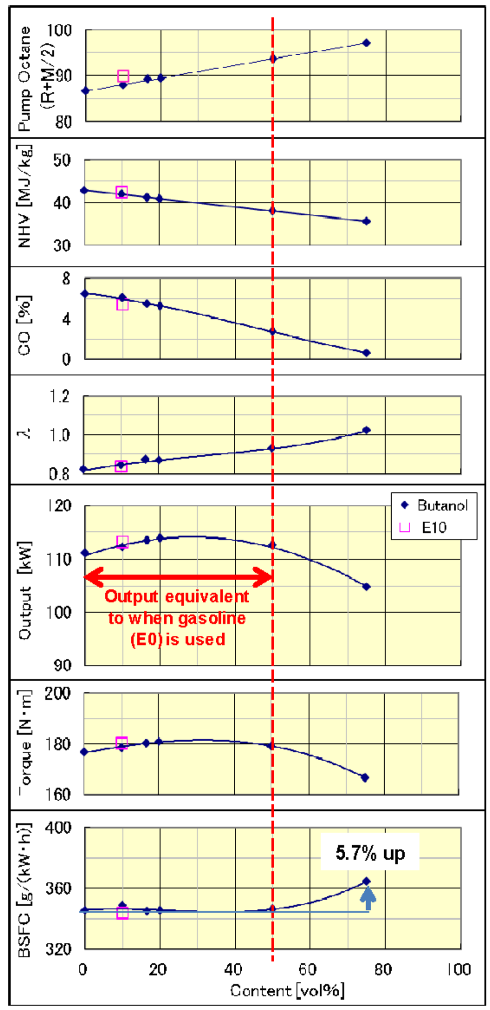

Fig. 3: Relationships of Mixing Ratio of Butanol and Performance

4.4. Exhaust gas emission characteristics

4.4.1. Purpose

To research the allowable mixing ratio of butanol, verify how butanol-mixed gasoline affects exhaust gas emissions and SFC characteristics.

4.4.2. Conditions

EPA 5-mode emission characteristics (40 CFR, Part 91, Subpart E, Table 2) are compared based on the performance test conditions in Table 2.

4.4.3. Judgment criteria

Mixing ratios of butanol that satisfy the exhaust gas emission regulation shall constitute an allowable range. Note that emissions at a butanol mixing ratio of 25 percent by volume or more are provided for reference purposes only because they were not measured in compliance with the measurement method specified in 40 CFR, Part 1065, Subpart I.

4.4.4. Result

In terms of exhaust gas emission characteristics, the allowable mixing ratio of butanol is 50 percent by volume or less.

Refer to Fig. 4 for the explanations of the statements provided below.

4.4.4.1. When the mix ratio of butanol is 50 percent by volume, emission levels are assumed to meet the regulation values as shown in the CO graph, THC+NOx graph and SFC graph, but SFC increases by 9.5% compared to when gasoline (E0) is used.

4.4.4.2. When the mix ratio of butanol is 16.5 percent by volume or less, both the emissions and SFC are equivalent to the levels with E10 gasoline, as shown in the CO graph, THC+NOx graph and SFC graph.

4.4.4.3. As shown in the CO graph and THC+NOx graph, CO emissions tend to decrease as the mixing ratio increases. As shown in the THC graph and NOx graph, however, THC does not increase and the increase in THC+NOx emissions is due to NOx.

4.4.4.4. As shown in the SFC graph and CO_2 graph, SFC and CO_2 emissions increase as the mixing ratio increases.

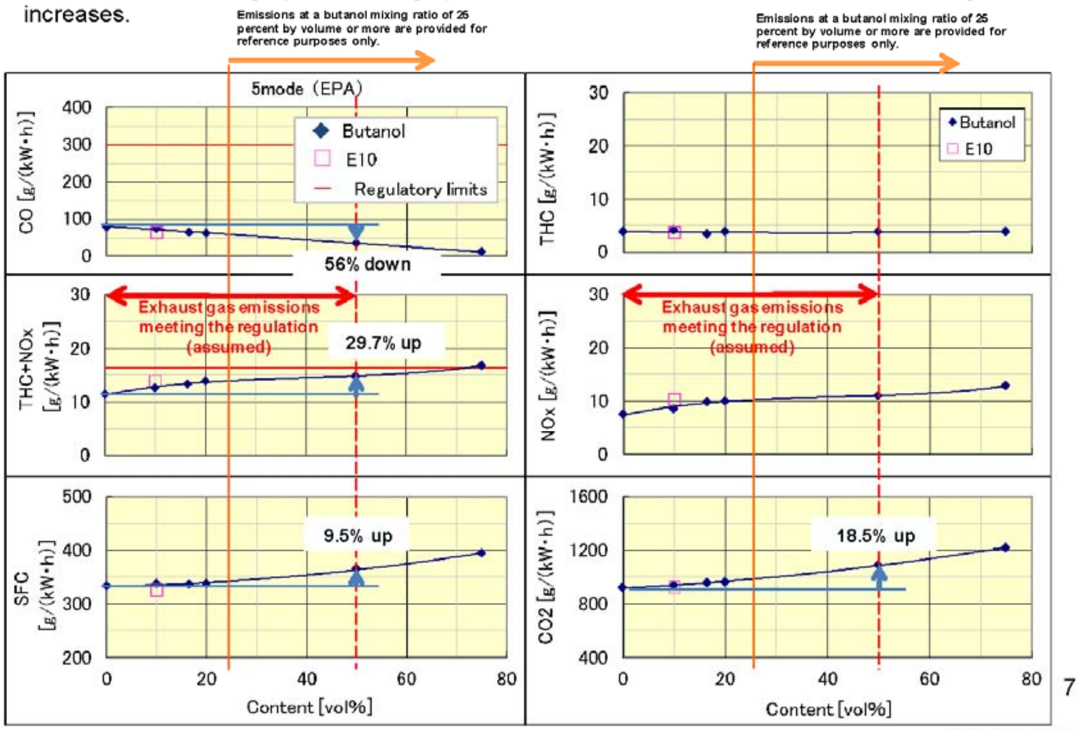

Fig. 4: Relationships of Mixing Ratio of Butanol and Exhaust Gas Emissions 130401905S

4.5. Cold startability (Ambient temperature: -15°C and 0°C)

4.5.1. Purpose

To research the allowable mixing ratio of butanol, verify how butanol-mixed gasoline affects cold startability at ambient temperatures of -15°C and 0°C.

4.5.2. Conditions

Verification was conducted for the winter season (when startability drops) considering the three scenarios below. Based on the performance test conditions in Table 2.

1. Reid Vapor Pressure (RVP)-equivalent condition
   Starting time was calculated using butanol-mixed gasoline adjusted to equivalent RVPs of summer-blend gasoline (E0) and E10 gasoline, from the normal condition test and abnormal condition test results shown below.
   Starting time was calculated at equivalent RVPs with reference to the RVPs of summer gasoline and E10 gasoline under the abnormal condition to be compared against (ASTM Class B).

2. Normal condition: Winter gasoline with high RVP was used.

3. Abnormal condition: Summer gasoline with low RVP was used.
   (The worst condition of making a cold start in winter using summer-blend fuel was assumed.)

4.5.3. Judgment criteria

An allowable mixing ratio of butanol is one that ensures startability equivalent to that of E10 gasoline, with an equivalent RVP.

4.5.4. Summary of cold startability (Ambient temperature: -15°C and 0°C)

When the RVP is adjusted to a level equivalent to the RVPs of fuels currently available on the market (E0 gasoline and E10 gasoline), cold startability is determined by the startability at -15°C at which the allowable mix ratio of butanol is 16.5 percent by volume.

The cold start test results are shown in Table 3.

	Ambient temperature	Condition of fuel used	Allowable mixing ratio of butanol	
Cold startability	-15℃	RVP- equivalent	0～16.5 vol%	← This restricts the allowable mixing ratio.
		Normal	0～25 vol%	
		Abnormal	0～(20 vol%)*	
	0℃	RVP- equivalent	0～25 vol%	
		Normal	0～30 vol%	
		Abnormal	0～20 vol%	

* The abnormal condition at -15°C represents a level at which the engine can still be started even when an inappropriate fuel is used. However, the time needed to start the engine increases as compared to when E0 gasoline or E10 gasoline is used.

Table 3: Cold Start Test Results

4.5.5. Result (Ambient temperature: -15°C)

When the RVP is adjusted to a level equivalent to the RVPs of fuels currently available on the market (E0 gasoline and E10 gasoline), the allowable mixing ratio of butanol that ensures cold startability at -15°C is 16.5 percent by volume or less.

Although up to 25 percent by volume is allowable in normal conditions of use, it is possible that summer gasoline could be used in winter after the engine has been in storage for a long period of time. Therefore, when the possibility of RVP adjustment is considered, startability problems do not occur as long as the mixing ratio is 16.5 percent by volume or less.

4.5.5.1. RVP-equivalent condition (-15°C) Refer to Fig. 5.

- When the mixing ratio of butanol is 16.5 percent by volume or less, startability is the same as when comparison fuels are used.
- When the mixing ratio of butanol is increased further, the oxygen content in fuel increases, therefore the starting time tends to increase due to the effect of the leaner air-fuel mixture at start.

The upper graph in Fig. 5 shows the RVP as a function of the mixing ratio of butanol, while the lower graph shows the starting time.

Blue ▲ : Summer E0 gasoline used as a comparison fuel (ASTM Class B)

Pink □ : Summer E10 gasoline used as a comparison fuel [Summer-blend gasoline into which ethanol is mixed at 10 percent by volume (ASTM Class B when mixed)]

Green ◆ : Starting time calculated at each mixing ratio by assuming a RVP-equivalent to the RVPs of summer E0 gasoline and E10 gasoline under the abnormal condition (ASTM Class B)

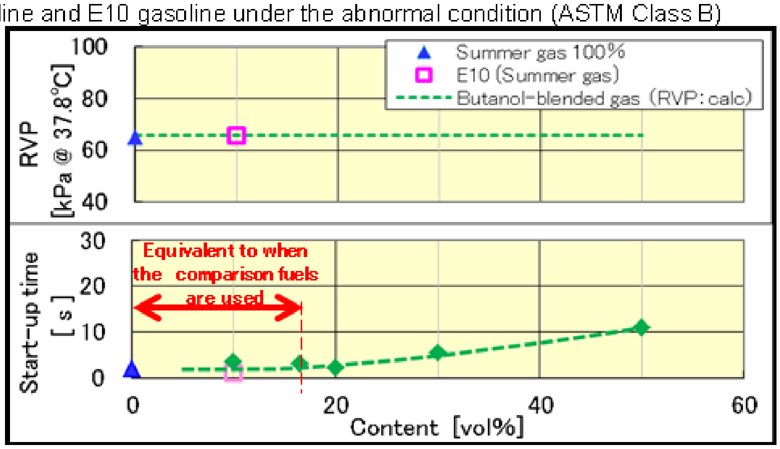

Fig. 5: Relationship of Mixing Ratio of Butanol and Startability under RVP-equivalent Condition [-15°C]

4.5.5.2. Normal condition (-15°C) Refer to Fig. 6.

- When the mixing ratio of butanol is 25 percent by volume or less, startability is the same as when comparison fuels are used.
- When the mixing ratio of butanol is increased without adjusting the RVP, the RVP drops and oxygen content in fuel increases, therefore the starting time tends to increase due to the effect of the leaner air-fuel mixture at start.

The upper graph in Fig. 6 shows the RVP as a function of the mixing ratio of butanol, while the lower graph shows the starting time.

Blue ▲ : Summer E0 gasoline used as a comparison fuel (ASTM Class B)

Pink □ : Summer E10 gasoline used as a comparison fuel [Summer gasoline into which ethanol is mixed at 10 percent by volume (ASTM Class B when mixed)]

Red ◆ : Fuel prepared by mixing butanol into winter gasoline [The RVP varies depending on the mixing ratio of butanol (ASTM Class D to B)]

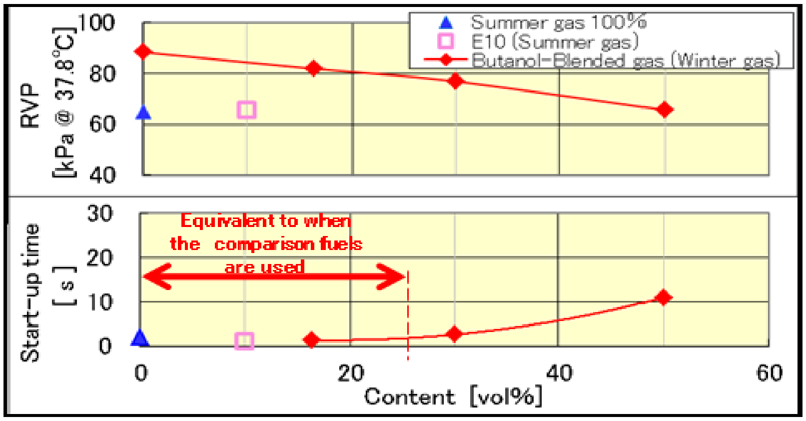

Fig. 6: Relationship of Mixing Ratio of Butanol and Startability under Normal Condition [-15°C]

4.5.5.3. Abnormal condition (-15°C) Refer to Fig. 7.

- As shown by the range enclosed by the red line, the time needed to start the engine increases when the mixing ratio of butanol is 20 percent by volume or less due to the effect of the lower RVP than the comparison fuels but the engine can still be started even when an inappropriate fuel is used.
- When the mixing ratio of butanol is increased further without adjusting the RVP, the RVP drops and oxygen content in fuel increases and therefore the starting time tends to increase due to the effect of the leaner air-fuel mixture at start.

The upper graph in Fig. 7 shows the RVP as a function of the mixing ratio of butanol, while the lower graph shows the starting time.

Blue ▲ : Summer E0 gasoline used as a comparison fuel (ASTM ClassB)

Pink □ : Summer E10 gasoline used as a comparison fuel [Summer gasoline into which ethanol is mixed at 10 percent by volume (ASTM Class B when mixed)]

Navy-blue ◆ : Fuel prepared by mixing butanol into summer gasoline whose volatility is lower than in the normal condition test (-15°C) [The RVP varies depending on the mixing ratio of butanol (ASTM Class A to Ultra A)]

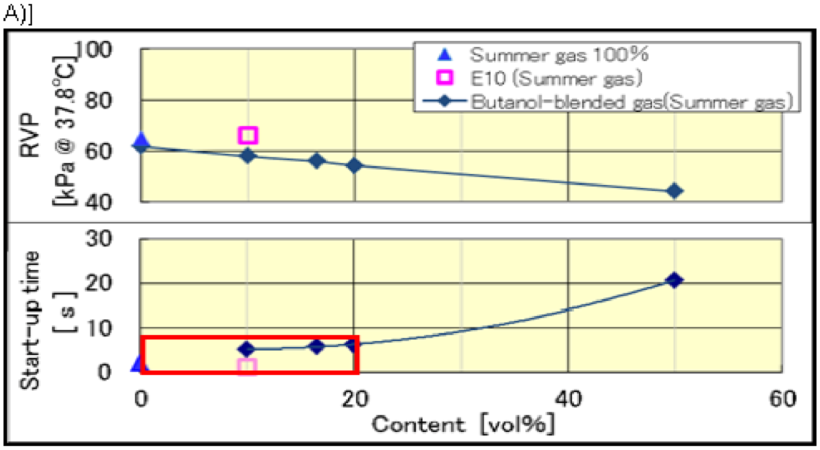

Fig. 7: Relationship of Mixing Ratio of Butanol and Startability under Abnormal Condition [-15°C]

4.5.6. Result (Ambient temperature: 0°C)

When the RVP is adjusted to a level equivalent to the RVPs of fuels currently available on the market (E0 gasoline and E10 gasoline), the allowable mixing ratio of butanol that ensures cold startability at 0°C is 25 percent by volume or less.

Although up to 30 percent by volume is allowable in normal conditions of use, it is possible that summer gasoline could be used in winter after the engine has been in storage for a long period of time. Therefore, when the possibility of RVP adjustment is considered, startability problems do not occur as long as the mixing ratio is 25 percent by volume or less.

4.5.6.1. RVP-equivalent condition (0°C) Refer to Fig. 8.

- When the mixing ratio of butanol is 25 percent by volume or less, startability is the same as when comparison fuels are used.
- When the mixing ratio of butanol is increased without adjusting the RVP, the RVP drops and oxygen content in fuel increases, and therefore the starting time tends to increase due to the effect of the leaner air-fuel mixture at start.

The upper graph in Fig. 8 shows the RVP as a function of the mixing ratio of butanol, while the lower graph shows the starting time.

Blue ▲ : Summer E0 gasoline used as a comparison fuel (ASTM ClassB)

Pink □ : Summer E10 gasoline used as a comparison fuel [Summer gasoline into which ethanol is mixed at 10 percent by volume (ASTM Class B when mixed)]

Green ◆ : Starting time calculated at each mixing ratio by assuming a RVP-equivalent to the RVPs of summer E0 gasoline and E10 gasoline under the abnormal condition (ASTM Class B)

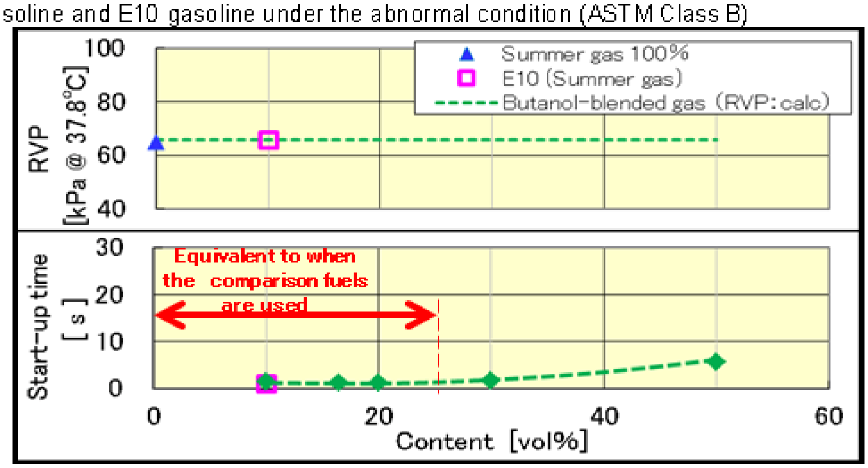

Fig. 8: Relationship of Mixing Ratio of Butanol and Startability under RVP-equivalent Condition [0°C]

4.5.6.2. Normal condition (0°C) Refer to Fig. 9.

- When the mixing ratio of butanol is 30 percent by volume or less, startability is the same as when comparison fuels are used.
- When the mixing ratio of butanol is increased without adjusting the RVP, the RVP drops and oxygen content in fuel increases, and therefore the starting time tends to increase due to the effect of the leaner air-fuel mixture at start.

The upper graph in Fig. 9 shows the RVP as a function of the mixing ratio of butanol, while the lower graph shows the starting time.

Blue ▲ : Summer E0 gasoline used as a comparison fuel (ASTM ClassB)

Pink □ : Summer E10 gasoline used as a comparison fuel [Summer gasoline into which ethanol is mixed at 10 percent by volume (ASTM Class B when mixed)]

Red ◆ : Fuel prepared by mixing butanol into winter gasoline [The RVP varies depending on the mixing ratio of butanol (ASTM Class D to B)]

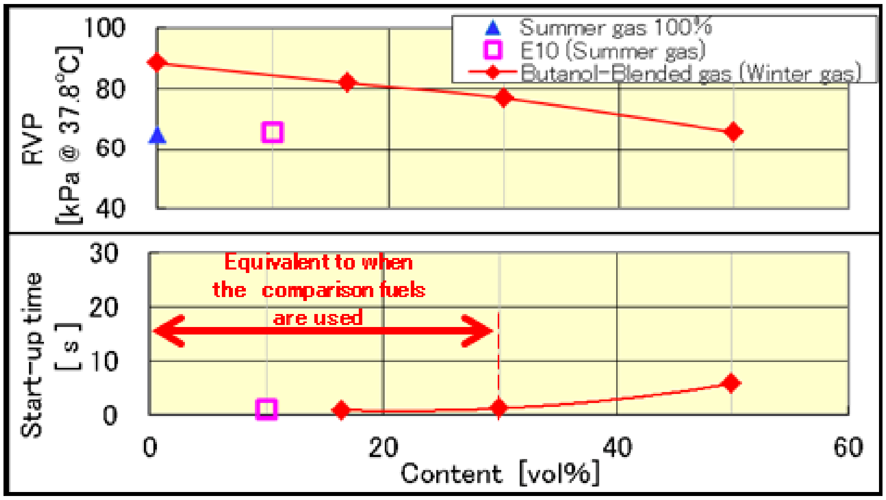

Fig. 9: __Relationship of Mixing Ratio of Butanol and Startability under Normal Condition [0°C]__

4.5.6.3. Abnormal condition (0°C) Refer to Fig. 10.

- When the mixing ratio of butanol is 20 percent by volume or less, startability is the same as when comparison fuels are used.
- When the mixing ratio of butanol is increased without adjusting the RVP, the RVP drops and oxygen content in fuel increases, and therefore the starting time tends to increase due to the effect of the leaner air-fuel mixture at start.

The upper graph in Fig. 10 shows the RVP as a function of the mixing ratio of butanol, while the lower graph shows the starting time.

Blue ▲ : Summer E0 gasoline used as a comparison fuel (ASTM ClassB)

Pink □ : Summer E10 gasoline used as a comparison fuel [Summer gasoline into which ethanol is mixed at 10 percent by volume (ASTM Class B when mixed)]

Navy-blue ◆ : Fuel prepared by mixing butanol into summer gasoline whose volatility is lower than in the normal condition test (-15°C) [The RVP varies depending on the mixing ratio of butanol (ASTM Class A to Ultra A)]

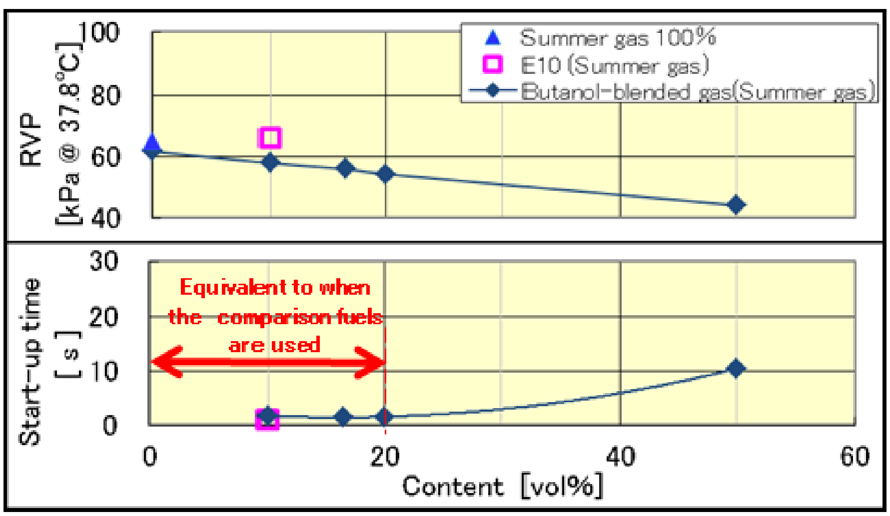

Fig. 10: __Relationship of Mixing Ratio of Butanol and Startability under Abnormal Condition [0°C]__

5. Component Function Test Results
5.1. Summary of fuel system component material tests
The test results are shown in Table 4.
The allowable mixing ratio of butanol for MFI outboard engines currently available on the market is 20 percent by volume or less, due to the restriction by resin materials.

Function test item		Allowable mixing ratio of butanol
Fuel system component materials	Resin/rubber materials	0 ~ 20 vol%
	Metal materials	0 ~ 50 vol%

← **This restricts the allowable mixing ratio.**

Table 4: Allowable Mixing Ratios Resulting from Fuel System Component Material Tests

5.1.1. Resin/rubber materials
5.1.1.1. Resin materials
The allowable mixing ratio of butanol is 20 percent by volume or less due to PA12 material as a restrictive factor. Other resin materials do not restrict the mixing ratio of butanol (allowable mixing ratio of butanol: 0 to 100 percent by volume).

5.1.1.2. Rubber materials
Rubber materials do not restrict the mixing ratio of butanol (allowable mixing ratio of butanol: 0 to 100 percent by volume).

5.1.2. Metal materials
5.1.2.1. Corrosion due to water
When the mixing ratio of butanol is 50 percent by volume or less, the corrosion is equivalent to when E0 to E10 gasoline is used.

5.1.2.2. Corrosion due to alcohol
Corrosion due to alcohol does not restrict the mixing ratio of butanol (allowable mixing ratio of butanol: 0 to 100 percent by volume).

5.2. Material test conditions

The fuel system component material test conditions are shown in Table 5.

Test item	Test component	Test equipment	Test fuel	Condition
【Swelling】 ・Resin materials HDPE/PA6/PA66/PA12 POM/PPS/PBTG30/PPG ・Rubber materials Binary FKM/tertiary FKM /FVMQ	Test piece	Soak tester	a. Gasoline : Indolene b. E10 Base Gasoline : Indolene , Ethanol : Derived from plants Mixing ratio : 10 vol% c. Butanol-mixed fuel Base Gasoline : Indolene , Butanol : Derived from petroleum Mixing ratio : 10,16.5,20,50,75,100 vol%	Soak temperature : 60℃
【Swelling】 ・Rubber materials NBR/NBR+PVC/H-NBR			a. FUEL C b. E10 Base fuel : FUEL C , Ethanol : Derived from plants Mixing ratio : 10vol% c. Butanol-mixing fuel Base Fuel : FUEL C, Butanol : Derived from petroleum Mixing ratio : 10,16.5,20,50,75,100 vol%	Soak temperature : Room temp(23℃)
【Corrosion due to water】 ・Metal material : Iron material	Test piece		a. Gasoline : Indolene b. E10 Base Gasoline : Indolene , Ethanol : Derived from plants Mixing ratio : 10 vol% c. Butanol-mixing fuel Base Gasoline : Indolene , Butanol : Derived from petroleum Mixing ratio : 20,50 vol%	・Soak temperature : 40℃ ・Soak in fuel to which water has been added. Amount of water added : 0.1,0.3,1.5wt%
【Corrosion due to alcohol】 ・Metal material : Aluminum material A6061	Test piece		a. Gasoline : Indolene b. E10 Base Gasoline : Indolene , Ethanol : Derived from plants Mixing ratio : 10 ,85vol% c. Butanol-mixing fuel Base Gasoline : Indolene , Butanol : Derived from petroleum Mixing ratio : 10,16.5,20,50,75,100 vol%	・Soak temperature : 100℃ /130℃ ・Sealed soak

Table 5: Fuel System Component Material Test Conditions

5.3. Resin/rubber materials

5.3.1. Purpose

To research the allowable mixing ratio of butanol, verify how butanol-mixed gasoline affects resin/rubber materials.

5.3.2. Conditions

Compare the maximum swelling amounts that cause deterioration of resin/rubber materials based on the material test conditions in Table 5.

5.3.3. Judgment criteria

Mixing ratios of butanol at which the maximum swelling amount remains equivalent to or less than the maximum swelling amounts with gasoline (E0) to E10 shall constitute an allowable range.

5.3.4. Result

In terms of resin/rubber materials, the allowable mixing ratio of butanol is 20 percent by volume or less, as restricted by PA12 (resin material).

The swelling test results of resin/rubber materials are shown in Table 6.

5.3.4.1. The swelling amount of resin material PA12 is equivalent to that by E10 when the mixing ratio of butanol is 20 percent by volume.

5.3.4.2. The swelling amounts of other resin/rubber materials remain at or below the level of swelling caused by E10, until the mixing ratio of butanol reaches 100 percent by volume, so no problem is anticipated.

Material			Mixing ration of butanol (percent by volume)						
Name		Detailed name	10	16.5	20	50	75	100	
Resin	HDPE	high-density polyethylene	OK	OK	OK	OK	OK	OK	
	PA6	polyamide 6	OK	OK	OK	OK	OK	OK	
	PA66	polyamide 66	OK	OK	OK	OK	OK	OK	
	PA12	polyamide 12	OK	OK	OK	NG	NG	NG	← This restricts the allowable mixing ratio.
	POM	Polyoxymethylene	OK	OK	OK	OK	OK	OK	
	PPS	Poly Phenylene Sulfide	OK	OK	OK	OK	OK	OK	
	PBTG30	30% glass fiber reinforced Poly Butylene Terephtalate	OK	OK	OK	OK	OK	OK	
	PFG	glass fiber reinforced Phenol Formaldehyde	OK	OK	OK	OK	OK	OK	
Rubber	NBR	nitrile rubber	OK	OK	OK	OK	OK	OK	
	NBR+PVC	nitrile rubber + Poly Vinyl Cloride	OK	OK	OK	OK	OK	OK	
	H-NBR	Hydrogenated nitrile rubber	OK	OK	OK	OK	OK	OK	
	Binary FKM	Binary fluoro-rubber	OK	OK	OK	OK	OK	OK	
	Tertiary FKM	Tertiary fluoro-rubber	OK	OK	OK	OK	OK	OK	
	FVMQ	Fluoro silicone rubber	OK	OK	OK	OK	OK	OK	

Table 6: Swelling Test Results of Resin/Rubber Materials

5.4. Metal materials

5.4.1. Corrosion due to water

5.4.1.1. Purpose

Verify how corrosion due to water changes with butanol-mixed gasoline.

5.4.1.2. Conditions

Understand phase separation of water added to a fuel and also compare the states of corrosion of metal materials (40°C for 120 hrs) after soaking based on the material test conditions in Table 5.

5.4.1.3. Judgment criteria

Research the mixing ratio that results in corrosion equivalent to when E0 to E10 gasoline is used.

5.4.1.4. Result

The mixing ratio of butanol that results in water corrosion equivalent to when E0 to E10 gasoline is used is within the range of 0 to 50 percent by volume.

Fig. 11 shows the comparison results of water phase separation when water is added.

5.4.1.4.1. With gasoline containing alcohol, added water disperses uniformly and phase separation does not occur easily.

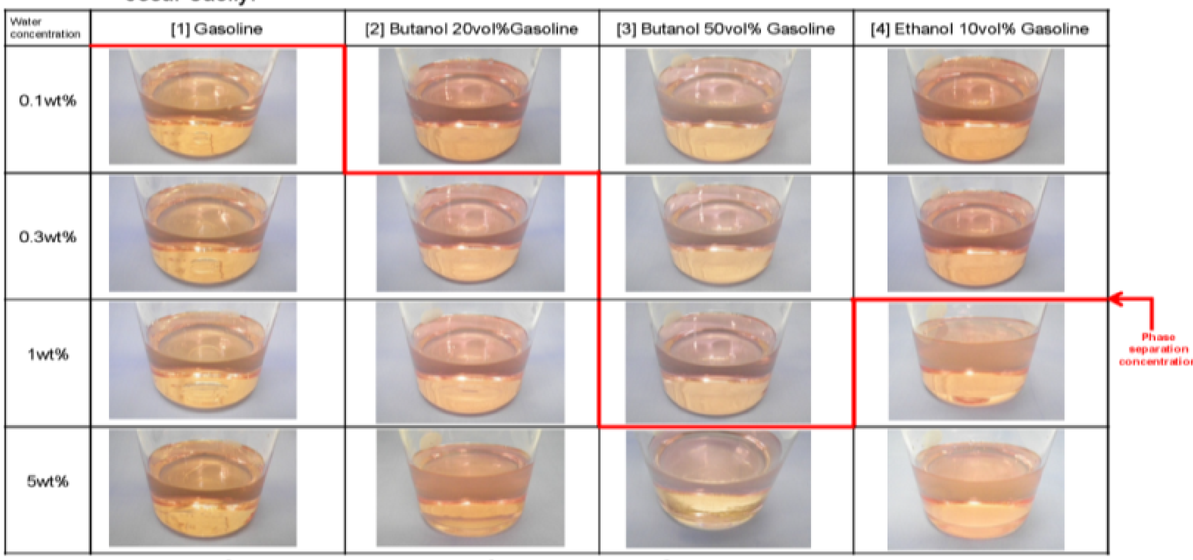

Fig. 11: Comparison Results of Water Phase Separation When Water Is Added

Fig. 12 shows the relationship of water phase separation and rust.

5.4.1.4.2. Corrosion occurs in a condition where water undergoes phase separation. (There is a correlation with the water phase separation shown in Fig. 11.)

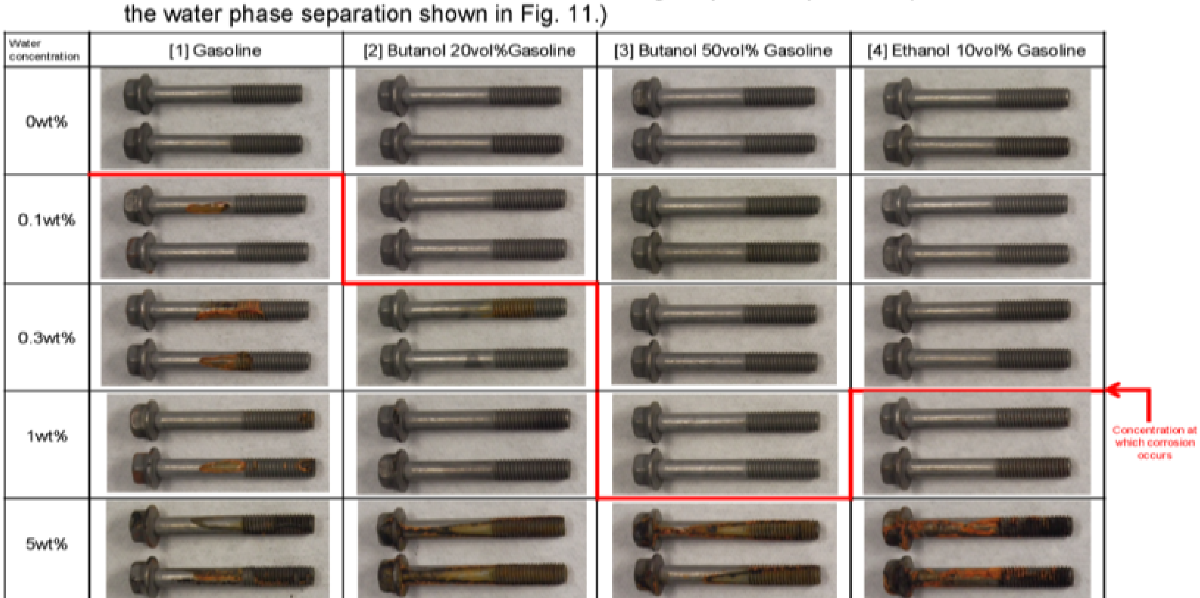

Fig. 12: Relationship of Water Phase Separation and Rust

5.4.2. Corrosion due to alcohol

5.4.2.1. Purpose

Verify the corrosion of aluminum material due to alcohol caused by gasoline containing butanol to determine the allowable mixing ratio of butanol.

5.4.2.2. Conditions

Soak aluminum material in sealed chamber based on the material test conditions in Table 5 and compare the aluminum corrosion reactions.

Soak temperatures: 100°C and 130°C

5.4.2.3. Judgment criteria

Maximum mixing ratios of butanol at which aluminum corrosion reaction does not occur constitutes an allowable range.

5.4.2.4. Result

Butanol does not cause an aluminum corrosion reaction and its mixing ratio is not restricted by this factor.
(Aluminum corrosion reaction does not occur in the range of mixing ratios of butanol from 0 to 100 percent by volume.)

5.4.2.4.1. Fig. 13 shows the alcohol corrosion test results.

Aluminum corrodes less due to butanol than ethanol, and alcohol corrosion reaction does not occur even when aluminum material is soaked for 1000 hours in 100% butanol at 130°C. Accordingly, no problem is anticipated.

Fuel / Soak temperature	Butanol						Ethanol	
	[1] 10 vol%	[2] 16.5 vol%	[3] 20 vol%	[4] 50 vol%	[5] 75 vol%	[6] 100 vol%	[7] 10 vol%	[8] 85 vol% (Reference)
100℃	Corrosion reaction did not occur for 350 hours, so the test was stopped.							
130℃	–	–	–	–	–	No Corrosion reaction for 1000 hours	No Corrosion reaction for 1000 hours	1h

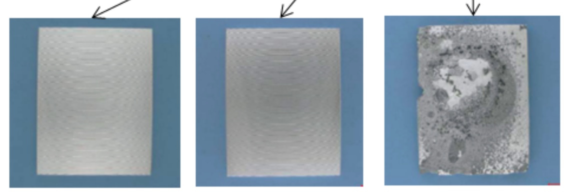

Fig. 13: <u>Alcohol Corrosion Test Results</u>

6. Conclusions

Engine performance and component function tests were conducted to understand the allowable mixing ratio of butanol.

6.1. Based on those test results, the mixing ratio of butanol to be used for the bench durability/reliability tests of MFI outboard engines currently available on the market shall be limited to 16.5 percent by volume.

The above was based on the cold startability at -15°C that results in the lowest allowable mixing ratio of butanol.

Table 7 shows a list of allowable mixing ratios of butanol obtained as a result of engine performance/component function tests.

Item			Allowable mixing ratio of butanol
Engine performance	Horsepower output characteristics		0～50 vol%
	Exhaust gas emission characteristics		0～(50 vol%)*
	Cold startability	-15°C	0～ 16.5 vol%
		0°C	0～25 vol%
Component function	Fuel system component materials	Resin and rubber materials	0～20 vol%
		Metal materials	0～50 vol%

← This restricts the allowable mixing ratio.

*** Emissions at a butanol mixing ratio of 25 percent by volume or more are provided for reference purposes only.**

Table 7: Engine Performance/Component Function Test Results (List of Allowable Mixing Ratios of Butanol)

6.2. Bench durability/reliability tests will be conducted using MFI outboard engines currently available on the market to make the final judgment regarding the compatibility of butanol-mixed fuel.

7. Considerations

The following insights were gained through the tests reported herein.

7.1. Volatility of fuel consisting of gasoline mixed with butanol

7.1.1. When butanol is mixed into base gasoline of the identical volatility, volatility of the mixed fuel tends to become lower than that of ethanol-mixed fuel.

7.1.2. From the viewpoint of cold startability, setting the RVP of butanol-mixed gasoline to the same levels as the RVPs of fuels currently available on the market (E0 gasoline and E10 gasoline) should result in similar starting performance.

7.2. Possibility of using higher mixing ratios of butanol for outboard engines

7.2.1. The allowable mixing ratio of butanol for MFI outboard engines available on the market was set as 16.5 percent by volume due to the restrictions by the following two items. It should be possible to increase the allowable mixing ratio of butanol to 24 percent by volume through additional testing and setting of proper specifications.

7.2.1.1. Cold startability: Change the starting specifications in the Engine Control Unit (ECU).

7.2.1.2. Allowable limit of resin material: Conduct additional verification on the allowable limit of PA12 material in gasoline containing 24 percent by volume of butanol. Or, change the specifications by adopting appropriate materials.

7.3. Future potential of butanol-mixed fuel

7.3.1. Alternative fuel for outboard engines

It was found that butanol was less detrimental to the materials used in outboard engines than ethanol. Butanol also has lower affinity with water and is therefore promising as an alternative fuel for outboard engines vulnerable to effects of water.

7.4. Reduction of CO_2

7.4.1. Oxygen content has the greatest influence on engine performance. The oxygen in butanol-mixed fuel is lower than ethanol-mixed fuel and the resulting higher energy density allows for use of higher mixing ratios than ethanol. Accordingly, CO_2 can be reduced. (The CO_2 reduction effect of E10 is roughly the same as that of gasoline containing 16.5 percent by volume of butanol.)

7.4.2. If gasoline containing 24 percent by volume of butanol can be used in the future, which contains oxygen equivalent to E15, petroleum-derived CO_2 emissions could possibly be reduced by as much as 20% as compared to when gasoline is used.

7.5. In conclusion, bio-butanol fuel is a very promising option as an alternative fuel to reduce CO_2 from outboard engines.

Appendix-1) Main Specifications of Test Outboard Engines

	BF150A	BF225A
Engine type	4stroke DOHC VTEC in-line 4-cylinder	4stroke OHC VTEC V6-cylinder
Displacement	2, 354cm^3 (143.6 cu-in)	3, 471cm^3 (211.7 cu-in)
Bore * stroke	87 * 99 mm (3.4 * 3.9 in)	89 * 93 mm (3.50 * 3.66 in)
Compression ratio	9.6 : 1	9.4 : 1
Rated power	111.9 kW (150 HP)	167.8 Kw (225 HP)
Full throttle range	5, 000~6, 000 r/min	5, 000~6, 000 r/min
Fuel supply system	Programmed fuel injection	Programmed fuel injection
Fuel injection system	Electronic control	Electronic control
Ignition system	Full transistorized, battery ignition	Full transistorized, battery ignition
Cooling system	Water cooling with thermostat	Water cooling with thermostat
Exhaust system	Water exhaust	Water exhaust
Fuel recommendations	**Unleaded gasoline (86 pump octane or higher)** Unleaded gasoline containing no more than 10% ethanol	**Unleaded gasoline (86 pump octane or higher)** Unleaded gasoline containing no more than 10% ethanol

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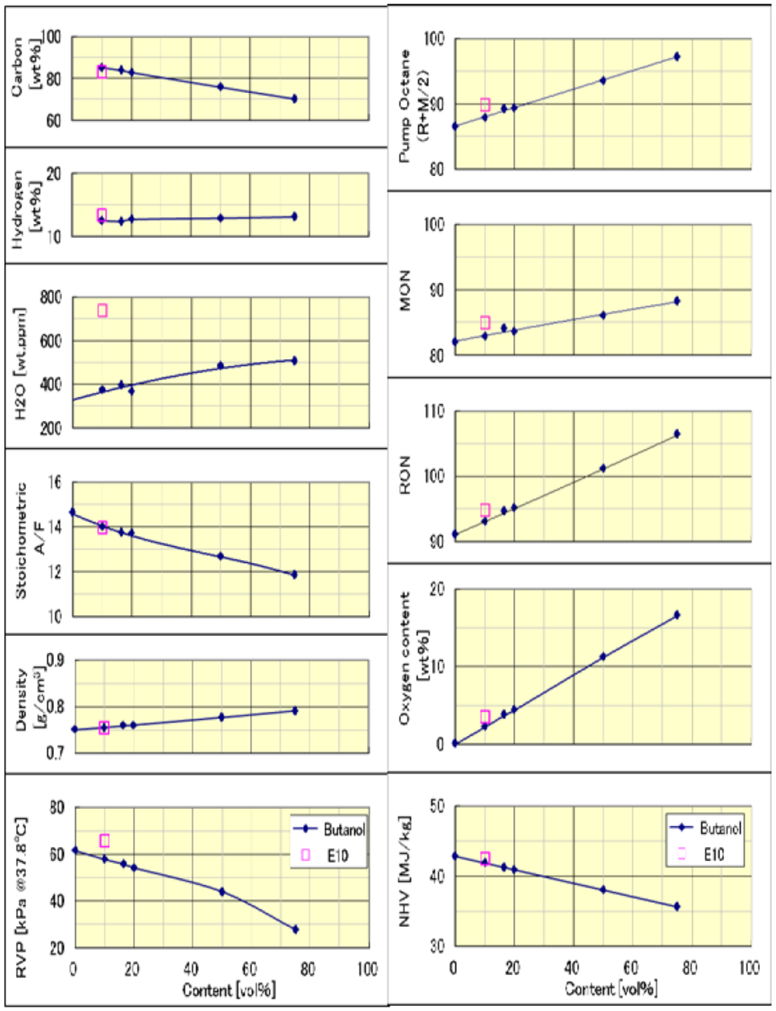
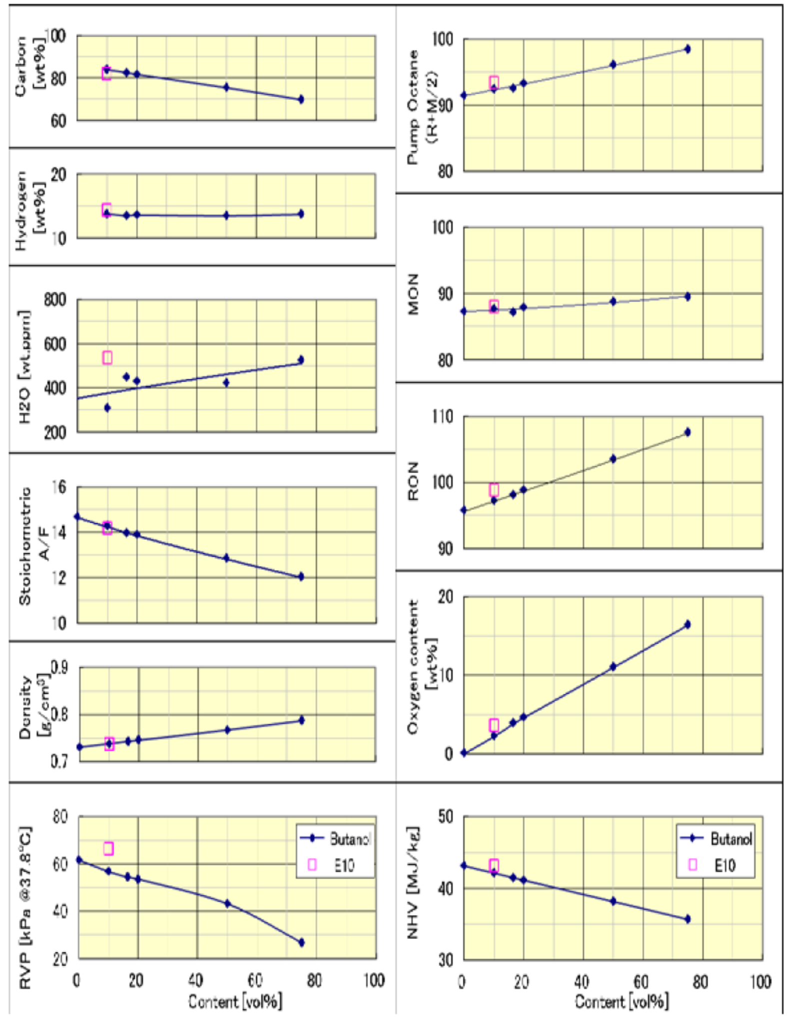
Appendix-2) Properties of Test Fuels

2.1 Regular gasoline base



2.2 Indolene gasoline base



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APPENDIX E. HONDA ENDURANCE TEST REPORT

USCG & HRA Joint Research
Compatibility of Outboard Engines with
Butanol-mixed Alternative Fuel
Endurance Tests **[Interim Report]**

September 20, 2013
Honda R&D Americas, Inc. Florida

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Table of Contents

i. Introduction

In early October of 2009, the President of the United States signed an Executive Order, which mandated that federal agencies make efforts to increase their energy efficiency and reduce greenhouse gas emissions. In response to this Executive Order, the U.S. Coast Guard began implementing strategies that will reduce their greenhouse gas emissions. Currently, the Coast Guard is exploring the use of alternative fuels, such as biobutanol, which will hopefully reduce their carbon footprint and comply with the new government regulations.

While biobutanol is more expensive to produce than ethanol, it may prove to be a more capable alcohol based fuel source than ethanol due to its non-corrosive properties, low hydrophilicity and its higher energy content. Due to the lack of familiarity with the use of biobutanol, it became clear that extensive testing would be necessary to validate the use of biobutanol as a fuel source.

In order to test the viability of biobutanol as an alternative fuel, a test plan was formed between the Coast Guard and Honda Marine. In early 2013, biobutanol testing began at the Honda Research and Development center located in Florida. In accordance with their collaborative research and development agreement, the Coast Guard agreed to supply the fuel for these tests and Honda agreed to supply the test engines and the test boat platforms. Testing was conducted over the course of four months.

1. Background

Ethanol based fuels in the United States have been reported to cause problems due to the tendency of ethanol to mix with water. As such, the validity of ethanol as an alternative fuel for marine applications is questionable. Therefore, the U.S. Coast Guard Research and Development Center and Honda R&D Americas, Inc. are conducting joint research into the compatibility of biobutanol-mixed fuel with outboard engines by focusing on the potential use of biobutanol as an alternative fuel according to the U.S. Executive Order that requires government agencies to investigate long-term strategies for reducing greenhouse gases.

2. Purpose

The purpose of this project is to ascertain the degree to which engine performance, component function and the durability/reliability of multiport fuel injected outboard engines would be influenced when a biobutanol-mixed fuel is used. Multiport fuel injection is hereinafter referred to as "MFI."

As shown in Fig. 1, this project consists of three steps. Step 1 will consist of engine performance tests and component function tests to be conducted by Honda. Step 2 will be the evaluation of the results of the tests in Step 1. Based on the results of Step 2 Honda will make an official recommendation to the Coast Guard concerning the use of biobutanol as a fuel source. If Honda determines that no adverse affects were caused by the use of biobutanol, Honda will officially recommend that the Coast Guard proceed with their yearlong test in Yorktown, Virginia.

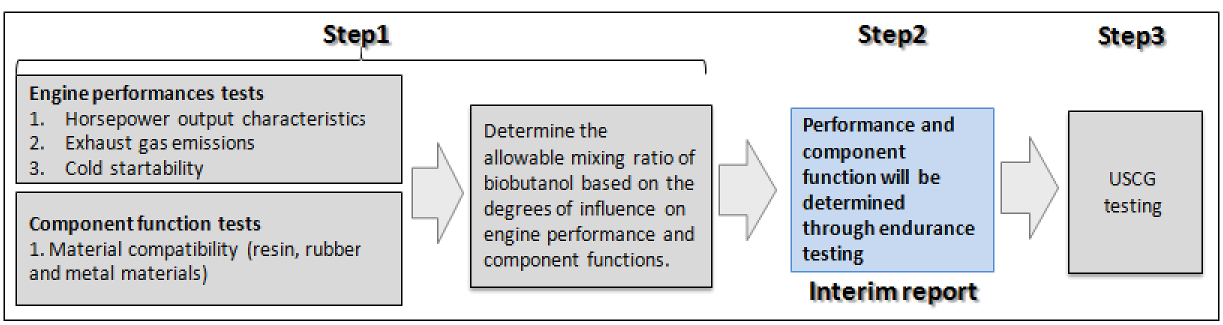

Fig. 1: Outline of This Interim Report

3. Items Checked for Determination of Allowable Mixing Ratio for Outboard Engines

The items in the left side chart in Figure 2 describe the different performance characteristics of biobutanol as compared to E0 and E10 and the subsequent determining factors for choosing biobutanol as a fuel source. The items in the right side of the chart in Figure 2 are the components and performance criteria that were evaluated during the endurance test to prove the viability of the use of biobutanol.

Item	Gasoline (E0)		Butanol		Ethanol (E10)
Energy density [%]	100	>	84	>	66
Oxygen content[wt %]	0	<	21.6	<	34.7
Stoichiometrical air-fuel mixture ratio	14.6	>	11.2	>	9
Pump Octane [(RON+MON) / 2]	86	<	98	<	102
Reid vapor pressure RVP [kPa]	44 - 78	>	3.4	<	16
Hygroscopicity property	None	<	Low	<	High
Alcohol content	Not contained	>	Contained	=	Contained

Items checked for determination of allowable mixing ratio	
Engine performance tests	• Horsepower output characteristics • Oil Consumption • Idle Stability •Cold Start ability
Component function tests	• Corrosion of metal components due to water
	• Corrosion of metal components due to alcohol • Swelling of resin and rubber components due to alcohol.

Fig. 2: Comparison of Fuel Characteristics and Items Checked for Determination of Allowable Mixing Ratio

4. Engine Endurance Test Results

4.1 Summary of Engine Endurance Tests

Two different endurance tests were conducted on two separate engines. The fuel used for both tests was an 87 octane conventional clear gasoline base mixed with biobutanol at a 16.1% ratio. The first engine was tested under conditions that simulate average use by a normal customer and the second engine was operated at full throttle for the duration of the test. Both engines were maintained according to factory recommendations. At the beginning and conclusion of the test, both engines were disassembled and sent to the Honda facility in Ohio for precision measurement. The engine measurement data was analyzed to determine if the use of biobutanol had any adverse effects or abnormal wear on specific engine components. The fuel system was analyzed by Honda R&D in Japan.

4.2 Engine Endurance Test Conditions

4.2.1 Endurance Engines

Both engines used in the biobutanol endurance tests were V6, 225hp Honda four stroke outboards. For this test, no special modifications were made to the engines. Prior to the beginning of the test, both engines were fully disassembled and the internal engine components were sent out for precision measurement at the Honda facility in Ohio. All fuel components that are associated with the engine were sent to an outside vendor for precision analysis before and after the test. See appendix 1 for specification information on the test engines.

4.2.2 Test Boats

Two test boat platforms were used during this test. The boat used for the normal use test mode was a 2005 Pro-Line 24' walkaround cuddy cabin, rigged with a single engine as shown in Figure 3. The boat used for the full throttle test mode was a 2005 S.A.F.E. 25' RB-S boat which is the same type of boat that is typically used by the U.S. Coast Guard as shown in Figure 4. The S.A.F.E boat is usually powered by two engines, however for this test only the starboard engine was used. This was done primarily to conserve fuel and reduce speed. The other engine was trimmed completely out of the water during the test and was not used.

Pro-Line 24 Walk	
Length	23'0"
Beam	8' 6"
Dry Weight	3,900 lbs
Max.HP	300HP
Transom Height	30"
Fuel Capacity	125gal.
Draft	14 in.

Figure 3: Normal use test boat

Safeboat 25 RB-S	
Length	25'0"
Beam	8' 6"
Dry Weight	7,000 lbs
Max.HP	450HP
Transom Height	30"
Fuel Capacity	105gal.
Draft	30 in.

Figure 4: Full throttle test boat

4.2.3 Rigging Setup Information

The normal use and full throttle engine were rigged on the respective boats as shown in figure 5 and figure 6.

Propeller	Solas 4x14.25x17
Trim Position	Level
Mounting Hole	First hole

Figure 5: Normal use engine rigging information

Propeller	Yamaha Saltwater Series II 3x15x15.25
Trim Position	Level
Mounting Hole	First hole

Figure 6: Full throttle engine rigging information

4.2.4 Endurance Test Mode

The normal use engine was operated at various throttle settings for 350 hours in order to closely approximate actual customer usage conditions. The full throttle engine was operated at full throttle for 300 hours. Due to fuel capacity restrictions, the full throttle boat was only able to be tested in 3 hour increments before refueling became necessary. Fig.7 represents the testing mode for the normal use engine and Fig. 8 represents the testing mode for the full throttle engine.

1 shift total 3 hours	
Time	**Mode**
20 minutes	Trolling (idle in gear)
24 Minutes	Cruise (4100-4200 r/min)
16 Minutes	Full Throttle (5500 r/min)
42 Minutes	Cruise (4100-4200 r/min)
28 Minutes	Trolling (idle in gear)
12 Minutes	Cruise (4100-4200 r/min)
8 Minutes	Full Throttle (5500 r/min)
21 Minutes	Cruise (4100-4200 r/min)
9 Minutes	Trolling (idle in gear)
180 Minutes	**Total**

Fig. 7: Normal use test sequence

1 shift total 3 hours	
Time	Mode
3 hours	Full Throttle

Fig. 8: Full Throttle test sequence

4.2.5 Progress of Endurance Test

Both endurance tests commenced on January 10, 2013. Regular maintenance and oil changes were performed throughout the tests as specified by the manufacturer. Each test was conducted in three hour intervals, twice daily. The first interval began around 8:30 in the morning and the second interval began after the boats were refueled, around 12:30pm. The duration of the test was conducted in the Indian River Lagoon between Sebastian, Florida and Cape Canaveral, Florida. A fuel supply issue toward the end of the test slowed down progress but in no way affected the results. Both tests were fully completed by April 15, 2013.

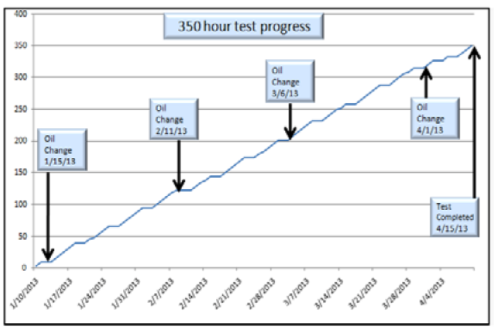

Fig. 9: Normal use test progress

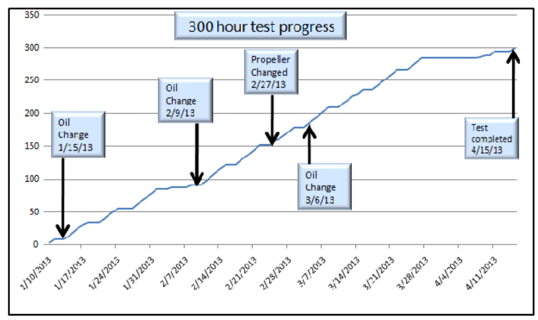

Fig. 10: Full throttle test progress

4.2.6 Environmental Conditions

Environmental data was taken on a daily basis for the duration of the test. As shown in Fig. 11, air temperature, relative humidity and barometric pressure were measured and recorded. Environmental conditions can affect engine performance. This data was monitored along with real-time engine data. If abnormal engine performance would have been detected, the environmental data would have been used to aid in troubleshooting the problem. There were no abnormal running conditions detected during this test on either engine.

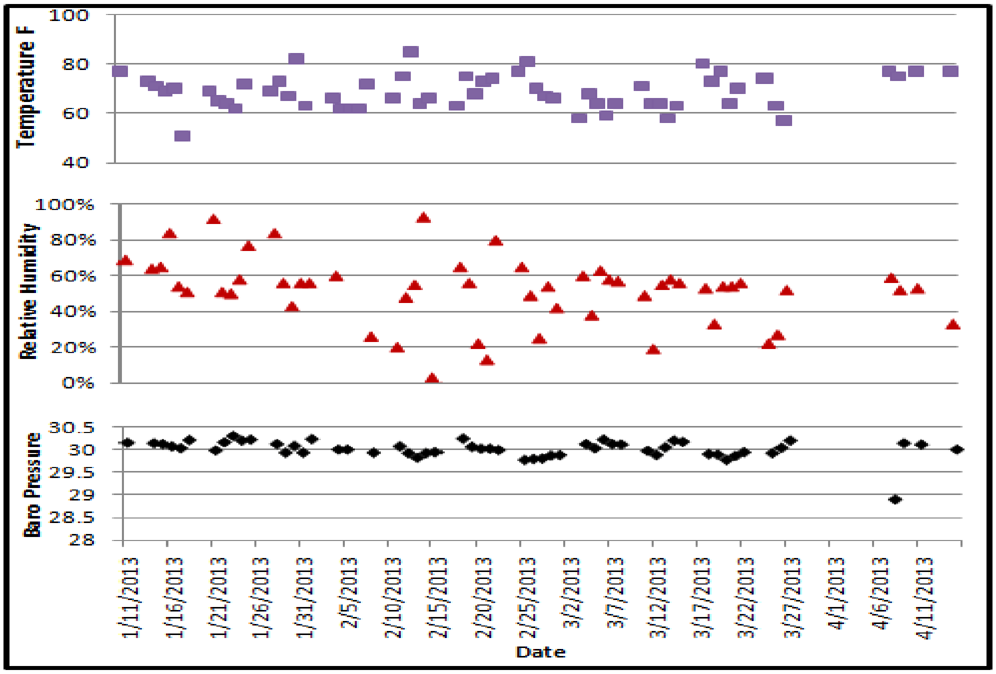

Fig. 11: Environmental Factor

4.2.7 Fuel Analysis

A 16.1% blend of biobutanol and gasoline was used in both engines for the entirety of this test. The base gasoline that was mixed with the butanol contained no ethanol. The biobutanol that was used is manufactured by Gevo and was delivered to a local third party fuel distributor in Melbourne, Florida. The biobutanol was mixed with the gasoline at the distributor's location and was stored there for the duration of the test. The mixed fuel was then delivered to Honda as needed, where it was stored onsite in a 500 gallon fuel container. To ensure that the fuel was mixed properly, a fuel sample was analyzed by an independent laboratory in San Antonio, Texas at the beginning and the end of the test.
See appendix 2 for specific data on the fuel analysis.

4.3 Fuel System Inspection

4.3.1 Purpose

To inspect the fuel system components of both test engines and determine what effect biobutanol has on those components.

4.3.2 Conditions

All fuel system components were evaluated by visual inspection and performance criteria at the beginning and the end of the test.

4.3.3 Judgment Criteria

The extent to which the fuel system components were affected by biobutanol will be judged based on findings from similar tests conducted with regular gasoline mixed with ethanol (E0-E10).

4.3.4 Results

Classification	Diagram number	Parts name	Engine	Check item			Judgment	Comment
				Performance	Pressure test	Wetted surface check		
Low pressure system	2	Fuel tube and Priming pump	Normal Use	—	ok	ok	ok	No deterioration and corrosion of fuel contact surface
			Full Throttle	—	ok	ok	ok	
	3,5,7,9, 11,15,17,28	Fuel tube Fuel pipe	Normal Use	—	ok	ok	ok	
			Full Throttle	—	ok	ok	ok	
	105	Fuel return solenoid valve	Normal Use	ok	ok	ok	ok	
			Full Throttle	ok	ok	ok	ok	
	102	Water Separator	Normal Use	ok	ok	ok	ok	
			Full Throttle	ok	ok	ok	ok	
	101	Fuel strainer	Normal Use	ok	ok	ok	ok	
			Full Throttle	ok	ok	ok	ok	
	104	Low-pressure fuel pump	Normal Use	ok	ok	ok	ok	
			Full Throttle	ok	ok	ok	ok	
Vent system	19,20	Air vent tube	Normal Use	—	ok	ok	ok	
			Full Throttle	—	ok	ok	ok	
	108	Strainer	Normal Use	ok	ok	ok	ok	
			Full Throttle	ok	ok	ok	ok	
	21	Joint	Normal Use	—	ok	ok	ok	
			Full Throttle	—	ok	ok	ok	
	22,23,24	Tube	Normal Use	—	ok	ok	ok	
			Full Throttle	—	ok	ok	ok	
	109	Check valve	Normal Use	ok	ok	ok	ok	
			Full Throttle	ok	ok	ok	ok	
High pressure system	103	Vapor separator assy	Normal Use	ok	ok	ok	ok	
			Full Throttle	ok	ok	ok	ok	
	13,14	Fuel hose	Normal Use	—	ok	ok	ok	
			Full Throttle	—	ok	ok	ok	
	25,26,27	Fuel hose joint	Normal Use	—	ok	ok	ok	
			Full Throttle	—	ok	ok	ok	
	106,107	Injector	Normal Use	ok	ok	ok	ok	
			Full Throttle	ok	ok	ok	ok	
	106,107	Fuel pipe	Normal Use	—	ok	ok	ok	
			Full Throttle	—	ok	ok	ok	
	107	Pressure regulator	Normal Use	ok	ok	ok	ok	
			Full Throttle	ok	ok	ok	ok	
Emission system	111	Oxygen sensor	Normal Use	ok	ok	ok	ok	
			Full Throttle	ok	ok	ok	ok	

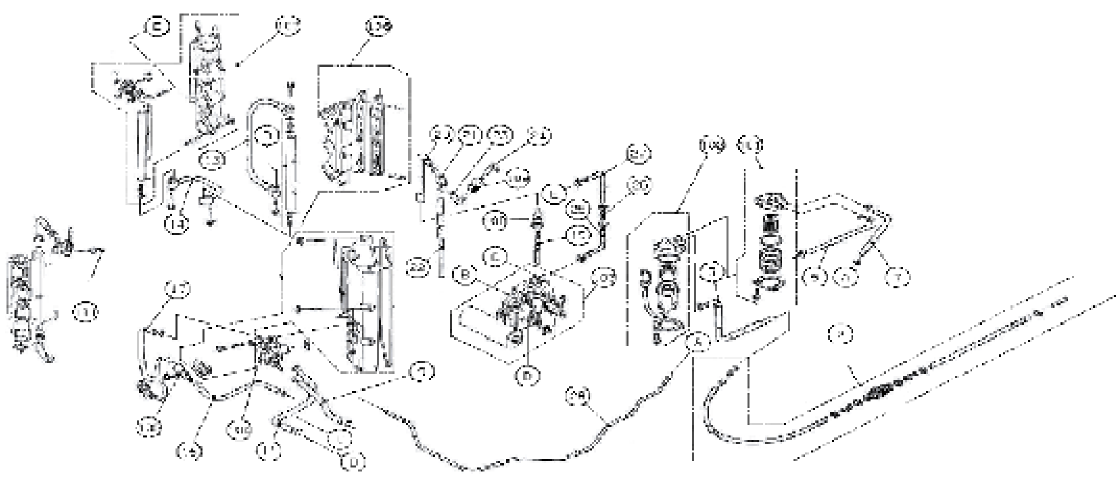

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Figure 12: Fuel system inspection

4.3.5 Conclusions

As evidenced by the results of the test, the use of biobutanol has had no adverse affects on any of the components of the fuel system. The results of the examination of the fuel system that used biobutanol were the same as similar tests using conventional E0-E10 gasoline.

4.4 Performance and Internal Engine Components Inspection

4.4.1 Purpose

To determine what affect the use of biobutanol has on performance and internal engine components.

4.4.2 Conditions

Engine performance and internal component measurement data was compared to the data taken before the start of the test and evaluated. Internal engine components were also visually inspected for damage. After a visual inspection was completed, each component was sent to the Honda facility in Ohio for precision measurement.

4.4.3 Judgment Criteria

Judgment is based on Honda standard specification.

4.4.4 Results

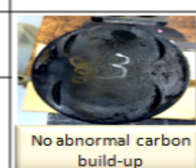
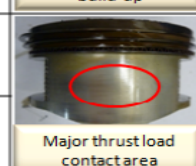
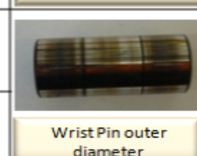
Performance Inspection

Item		Result		Comment
Part Location	Part Area	Normal Use Engine	Full Throttle Engine	
Performance	Power (Top Speed and Engine Speed)	No Significant reduction (Top speed and r/min)	No Significant reduction (Top speed and r/min)	Within Manufacturers Specifications
	Oil Consumption	No significant difference in oil consumption between the beginning and end of the test	No significant difference in oil consumption between the beginning and end of the test	Within Manufacturers Specifications
	Idle Stability	No significant change to idle stability between the beginning and the end of the test	No significant change to idle stability between the beginning and the end of the test	Within Manufacturers Specifications
	Start ability	No significant change to start ability between the beginning and the end of the test	No significant change to start ability between the beginning and the end of the test	Within Manufacturers Specifications

Figure 13: Performance

Internal Engine Components Inspection

Item				Result			Comment
Part Location	Part Area	Specific Part	Specific Part Area	Engine	Measurement	Visual	
Piston	Ring	All pistons	Are the rings stuck or free?	Normal use Engine	ok		All rings were free
				Full Throttle engine	ok		
		1st Piston Ring	Width	Normal use Engine	ok		All measurements were within specification
				Full Throttle engine	ok		
			Radial wall thickness	Normal use Engine	ok		
				Full Throttle engine	ok		
			Free gap	Normal use Engine	ok		
				Full Throttle engine	ok		
			Tension	Normal use Engine	ok		
				Full Throttle engine	ok		
		2nd Piston Ring	Width	Normal use Engine	ok		All measurements were within specification
				Full Throttle engine	ok		
			Radial wall thickness	Normal use Engine	ok		
				Full Throttle engine	ok		
			Free gap	Normal use Engine	ok		
				Full Throttle engine	ok		
			Tension	Normal use Engine	ok		
				Full Throttle engine	ok		

Item				Result			Comment
Part Location	Part Area	Specific Part	Specific Part Area	Engine	Measurement Result	Visual	
Piston	Piston Crown	All pistons	Carbon build up levels	Full Throttle	ok		Carbon build up level within tolerances
				Normal Usage	ok		
	Piston Skirt	Thrust load area	Major thrust load area	Full Throttle	ok		Minimal wear on the major thrust load contact area
				Normal Usage	ok		
	Wrist Pin	Piston side	Inside diameter	Full Throttle	ok		All measurements were within specification
				Normal Usage	ok		
		Connecting rod side	Outside diameter	Full Throttle	ok		All measurements were within specification
				Normal Usage	ok		

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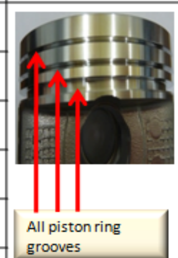
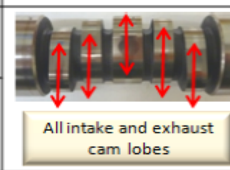
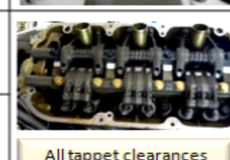
Item				Result			Comment
Part Location	Part Area	Specific Part	Specific Part Area	Engine	Measurement	Visual	
Piston	Ring	Oil Ring	Width	Normal Use Engine	ok		All measurements were within specification
				Full Throttle Engine	ok		
			Radial wall thickness	Normal Use Engine	ok		
				Full Throttle Engine	ok		
			Free gap	Normal Use Engine	ok		
				Full Throttle Engine	ok		
			Tension	Normal Use Engine	ok		
				Full Throttle Engine	ok		
		Piston ring groove	1st piston ring	Normal Use Engine	ok		All measurements were within specification
				Full Throttle Engine	ok		
			2nd piston ring	Normal Use Engine	ok		
				Full Throttle Engine	ok		
			Oil ring	Normal Use Engine	ok		
				Full Throttle Engine	ok		

Item				Result			Comment
Part Location	Part Area	Specific Part	Specific Part Area	Engine	Measurement	Visual	
Cylinder Head	Cam shaft	Cam Shaft	Cam lobe height	Full Throttle engine	ok		All measurements were within specification
				Normal Use Engine	ok		
		Cam Shaft Journal	Outside diameter	Full Throttle engine	ok		All measurements were within specification
				Normal Use Engine	ok		
		Cylinder Head Cam Shaft Journal	Inside diameter	Full Throttle engine	ok		All measurements were within specification
				Normal Use Engine	ok		
	Valve train	Tappet	Clearance	Full Throttle engine	ok		All measurements were within specification
				Normal Use Engine	ok		

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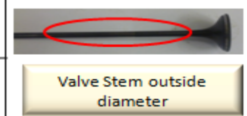
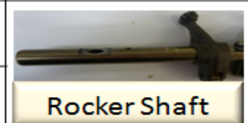
Item					Result		Comment
Part Location	Part Area	Specific Part	Specific Part Area	Engine	Measurement	Visual	
Cylinder Head	Valve	Valve stem (All Valve Stems)	Outside diameter	Normal Use engine	ok		All measurements were within specification
				Full Throttle Engine	ok		
		Valve guides Intake and Exhaust	Inside diameter	Normal Use engine	ok		
				Full Throttle Engine	ok		
		Valve seat (All Valves)	wear	Normal Use engine	ok		
				Full Throttle Engine	ok		
	Rocker arm	Rocker shaft (All Rocker shafts)	Outside diameter	Normal Use engine	ok		All measurements were within specification
				Full Throttle Engine	ok		
		Rocker arm (All Rocker Arms)	Inside diameter	Normal Use engine	ok		
				Full Throttle Engine	ok		

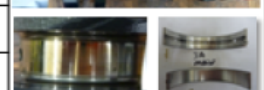
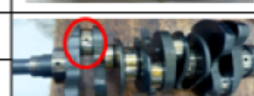
Item					Result		Comment
Part Location	Part Area	Specific Part	Specific Part Area	Engine	Measurement	Visual	
Cylinder Block	Cylinder Sleeve	Bore	Inside diameter	Normal Use	ok		All measurements were within specifications
				Full Throttle	ok		
	Crank Main bearing	Cylinder Block side	Inside diameter	Normal Use	ok		All measurements were within specifications
				Full Throttle	ok		
		Crank side	Outside diameter	Normal Use	ok		
				Full Throttle	ok		
		Oil clearance		Normal Use	ok		
				Full Throttle	ok		
	Crank Connecting rod bearing	Connecting rod side bearing diameter	Inside diameter	Normal Use	ok		All measurements were within specifications
				Full Throttle	ok		
		Crank side	Outside diameter	Normal Use	ok		
				Full Throttle	ok		
		Oil clearance		Normal Use	ok		
				Full Throttle	ok		
	Thrust bearing	Upper and Lower thrust bearing	Thickness	Normal Use	ok		All measurements were within specifications
				Full Throttle	ok		

Figure 14: Engine Measurement

4.4.5 Conclusions

Power, performance, top speed and oil consumption were all within acceptable limits on both engines at the conclusion of the test.

Carbon build up on the piston crowns and the combustion chambers was within acceptable limits. Visually there was no apparent damage or excessive wear to any of the internal engine components. The acceptable condition of the internal engine components was validated by the precision measurement that took place at the Honda facility in Ohio. All measurements were within acceptable limits. We can therefore determine that no adverse affects to the internal engine components were caused by the use of biobutanol.

4.5 Oil Performance

4.5.1 Purpose

To investigate and determine what effect biobutanol mixed fuel will have on engine oil when used in a MFI Honda outboard engine.

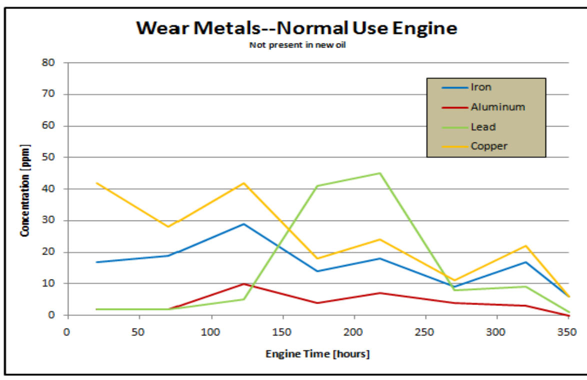
4.5.2 Conditions

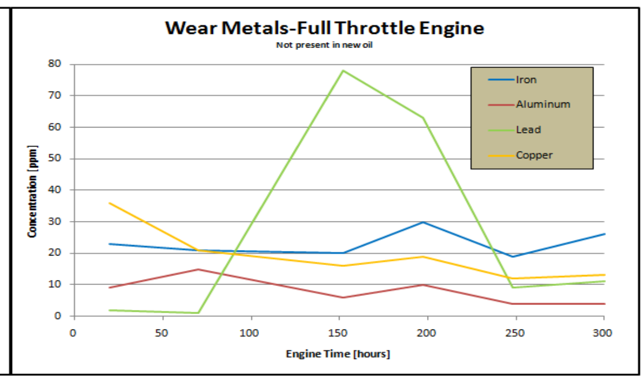
Engine oil was sampled approximately every 50 hours during the endurance test and sent to an oil analysis laboratory.

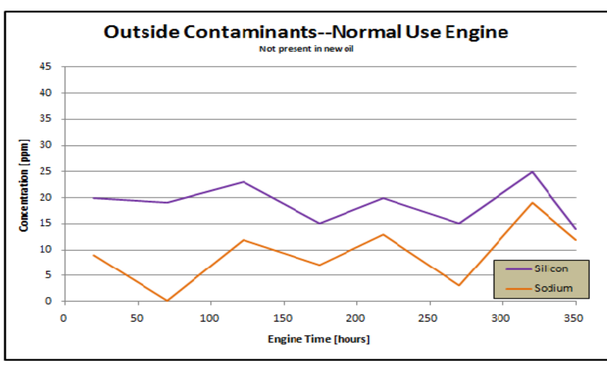
4.5.3 Judgment Criteria

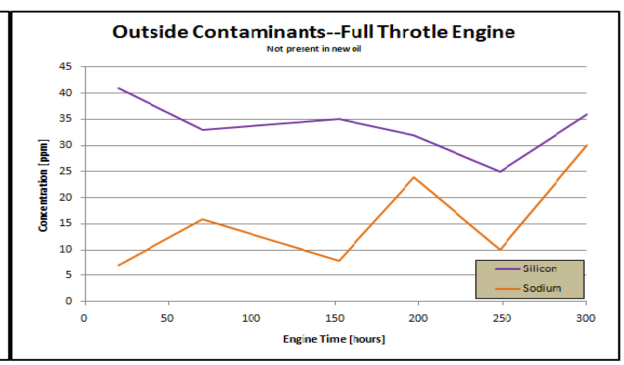
Evaluate findings to determine if biobutanol mixed fuel has a negative effect on oil integrity.

4.5.4 Results









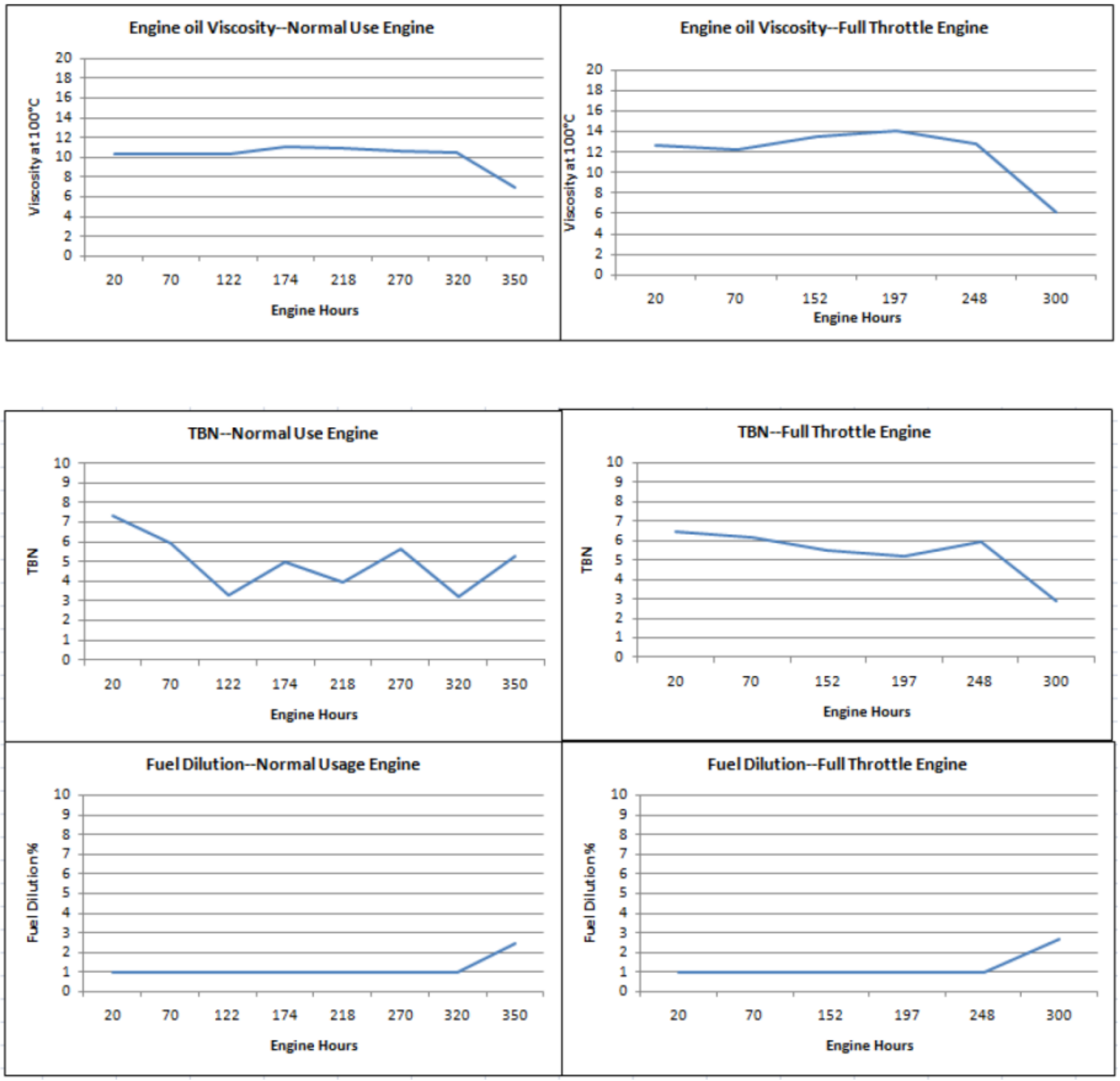


Figure 15: Oil Analysis

4.5.1 Conclusions

There was no negative effect on the engine oil that was caused by the use of biobutanol.

5. Test Conclusion

From the information gathered and analyzed in the above tests, we can conclude that the use of biobutanol, mixed with gasoline at a 16.1% ratio, as a fuel will not adversely affect any of the systems of the Honda MFI four stroke outboard engine. Judging by the data gathered in this test, it is the opinion of Honda R&D that the U.S. Coast Guard can proceed with their yearlong endurance test in Yorktown, Virginia.

6. Considerations

The following insights were gained through the tests reported herein.

6.1 This interim report proves the reliability and durability of the Honda MFI four stroke outboard when using gasoline mixed with biobutanol at a 16.1% ratio through actual endurance testing. An acceptable ratio of 16.1% was determined through performance and function testing. No engine modifications are necessary for a 16.1% blend of biobutanol fuel to work well with the Honda engine.

6.2 Based on performance, function and endurance testing, biobutanol fuel proved to be a very promising option as an alternative fuel to reduce CO_2 from outboard engines and was not found to have any significant negative effects.

6.3 Honda is pleased to be involved in a project that assists the USCG in reducing their greenhouse gas emissions and to assist in lessening its impact on the environment

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Appendix-1) Main Specifications of Test Outboard Engines

	BF 225A
Engine Type	4stroke OHC VTEC V6-Cylinder
Displacement	3471cm^3 (211.7cu-in)
Bore X Stroke	89 X 93 mm (3.50 X 3.66in)
Compresion ratio	9.4 : 1
Rated Power	167.8 kw (225 HP)
Full Throttle Range	5000~6000 r/min
Fuel supply system	Programed fuel injection
Fuel injection system	Electronic control
Ignition system	Full transistorized, battery ignition
Cooling system	Water cooling with thermostat
Exhaust system	Water exhaust
Fuel recommendations	Unleaded gasoline (86 pump octane or higher) Unleaded gasoline containing no more than 10% ethanol
Oil recommendations	Honda SAE 10W-30 FC-W

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Appendix-2) Properties of Test Fuels

Fuel analysis tests were conducted by an independent laboratory in San Antonio, Texas.

Sample taken in January 2013

D5191	RVP	psi	10.49
D130 Fuels	Copper		1a
D1319	Aromatic	%	21.9
	Olefins	%	13.6
	Saturate	%	64.5
	CorrArom	%	18.53
	CorrOlef	%	11.51
	CorrSat	%	54.58
D240G	BTUHeat	BTU/lb	19216
	MJHeat	MJ/kg	44.697
	CALHeat	cal/g	10675.7
D240N	BTUHeat	BTU/lb	17960
	MJHeat	MJ/kg	41.775
	CALHeat	cal/g	9977.8
D2699Mdp	RON	Inch-lbs	94.3
D2700Mdp	MON	Inch-lbs	84.2
D3231	Phosphor	mg/L	0.44
D3237	Lead	gr/Gal	<0.001
D3606EPA	Benzene	Vol%	0.47
	Toluene	Vol%	3.38
D381	UnWshdGm		17
	WashdGum		0.4
D3831	Manganes	mg/l	<0.2
D4052s	API@60F		60
	SPGr@60F		0.7391
	Dens@15C	g/ml	0.7388
D4176	ClrBrt		C&B
	Particul		no
	FreeWatr		no
	Haze		1
D525	RunTime	min	1440

	BreakY/N		NO BREAK
D5291 CH	Carbon	wt%	82.6
	Hydrogen	wt%	13.77
D5453	Sulfur	ppm	35.4
D5599	EtOHVol	Vol%	<0.1
	EtOHWt	wt%	<0.1
	iBAVol	Vol%	15.349
	iBAWt	wt%	16.7342
	TtlWt	wt%	3.61
D6304	Water%	%	0.140434
	Water	mg/kg	1403
D86	IBP	deg F	86.3
	Evap_5	degF	96.6
	Evap_10	degF	111.7
	Evap_15	degF	124.2
	Evap_20	degF	135.5
	Evap_30	degF	157.7
	Evap_40	degF	179.2
	Evap_50	degF	197.5
	Evap_60	degF	210.6
	Evap_70	degF	221.8
	Evap_80	degF	253.9
	Evap_90	degF	311.3
	Evap_95	degF	339.3
	FBP	degF	387.5
	Recoverd	mL	95.1
	Residue	mL	0.5
	Loss	mL	4.4
E659	AIT	deg F@	599
	AITLag	seconds	9

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Sample taken in April 2013

D5191	RVP	psi	9.65
D130 Fuels	Copper		1a
D1319	Aromatic	%	24
	Olefins	%	13.1
	Saturate	%	62.9
	CorrArom	%	20.39
	CorrOlef	%	11.13
	CorrSat	%	53.44
D240G	BTUHeat	BTU/lb	19241
	MJHeat	MJ/kg	44.755
	CALHeat	cal/g	10689.4
D240N	BTUHeat	BTU/lb	17966
	MJHeat	MJ/kg	41.789
	CALHeat	cal/g	9981.1
D2699Mdp	RON	inch-lbs	94.6
D2700Mdp	MON	Inch-lbs	84.2
D3231	Phosphor	mg/L	0.7
D3237	Lead	gr/Gal	<0.001
D3606EPA	Benzene	Vol%	0.49
	Toluene	Vol%	18
D381	UnWshdGm		28
	WashdGum		0.5
D3831	Manganes	mg/l	<0.2
D4052	API@60F		59
	SPGr@60F		0.7429
	Dens@15C	g/ml	0.7427
D4176	ClrBrt		C&B
	Particul		no
	FreeWatr		no
	Haze		1
D525	RunTime	min	1440

	BreakY/N		NO BREAK
D5291 CH	Carbon	wt%	82.7
	Hydrogen	wt%	13.97
D5453	Sulfur	ppm	36.6
D5599	iBAVol	Vol%	15.0385
	iBAWt	Wt%	16.3118
	TtlWt	Wt%	3.52
D6304	Water%	%	0.13372
	Water	mg/kg	1337
D86	IBP	deg F	83.2
	Evap_5	degF	100.6
	Evap_10	degF	117.7
	Evap_15	degF	129.3
	Evap_20	degF	140.4
	Evap_30	degF	161.9
	Evap_40	degF	182.6
	Evap_50	degF	199.1
	Evap_60	degF	210.6
	Evap_70	degF	222.4
	Evap_80	degF	259.7
	Evap_90	degF	313.2
	Evap_95	degF	340.9
	FBP	degF	380.9
	Recoverd	mL	96.3
	Residue	mL	1.1
	Loss	mL	2.6
E659	AIT	deg C	300
	AITLag	seconds	12.7
	CFT	deg C	0
	CFTLag	seconds	0
	BaroPres	mm Hg	741.9
	RTT	deg C	254

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